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Climate-Driven Impacts of Groundfish on Food Webs in the Northern Bering Sea

Xuehua Cui
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a dissertation written by Xuehua Cui entitled "Climate-Driven Impacts of Groundfish on Food Webs in the Northern Bering Sea." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Ecology and Evolutionary Biology.

Jacqueline M. Grebmeier, Major Professor

We have read this dissertation and recommend its acceptance:

Lee W. Cooper, David A. Etnier, Richard J. Strange, William L. Seaver

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Carolyn R. Hodges
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Climate-driven impacts of groundfish on food webs in the northern Bering Sea

A Dissertation

Presented for the

Doctor of Philosophy

Degree

The University of Tennessee, Knoxville

Xuehua Cui

August 2009

Dedication

This dissertation is dedicated to my husband and son.

Acknowledgements

I would like to thank my supervisors Dr. Jacqueline M. Grebmeier and Dr. Lee W. Cooper who gave me such a precious opportunity to undertake work on this project. This work would not have been possible without their consistent support and guidance in every step, from the preparation of the project to the final manuscript. Their hard work and knowledge have been such an inspiration for me. I would also like to acknowledge my other committee members for advice and comments, especially the statistical advice and time from Dr. William L. Seaver. I would also like to thank Dr. James R. Lovvorn who gave valuable suggestions and provided many related papers to improve my research perspective.

I would also like to thank Catherine W. Mecklenburg who helped to confirm the fish identification, Rebecca Brown who assisted with prey identification in the lab work, and Wes Jones and Sang H. Lee who provided fish samples for stable isotope analyses through the Norton Sound Economic Development Corporation (NSEDC) in summer 2006 from the R/V *Pandalus* (NSEDC06) and from the Japanese T/S *Oshoro-Maru* research cruise in summer 2007, respectively. I would also like to thank Zhenghua Li who made the stable carbon and nitrogen isotope ratio determinations. I want to also thank the captains and crew of the USCGC *Healy* and the many people who assisted with fish sampling.

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Abstract

Groundfish distributions were examined in spring 2006 and 2007 in the northern Bering Sea around St. Lawrence Island (SLI). Arctic cod (*Boreogadus saida*), Bering flounder (*Hippoglossoides robustus*), and snailfish (Liparidae) were the dominant species south of SLI, whereas Arctic alligatorfish (*Ulcina olrikii*) and Arctic staghorn sculpin (*Gymnocanthus tricuspis*), or shorthorn sculpin (*Myoxocephalus scorpius*) were dominant north of SLI. The results indicate that bottom water (or water column) chlorophyll *a* and sediment parameters had greater influence on fish distribution in 2006 (cold, pre-bloom conditions), whereas bottom water temperature and sediment grain size were more important in 2007 (warm, bloom conditions) among a total of 14 environmental variables that were analyzed. These findings suggest strong linkages between physical conditions (e.g. water temperature and hydrography as it affects sediment grain size) and biological conditions (e.g. bloom status) in structuring fish communities in the northern Bering Sea.

The diet and feeding relationship of six dominant groundfish, specifically Arctic cod, Bering flounder, snailfish, Arctic staghorn sculpin, Arctic alligatorfish, and shorthorn sculpin in the northern Bering Sea were studied using stomach content data in spring 2006 and 2007. All of Bering flounder had empty stomachs. Amphipods were the primary prey in five fish species

characterized by feeding narrow niches except snailfish, which consumed a diverse diet. Arctic cod was the only occasional pelagic feeder; all the other fish studied were benthic feeders. High diet overlap was found among some fish species; however, competition was likely reduced by differences in feeding strategies and available food resources.

Stable carbon and nitrogen isotopes of groundfish and their potential prey items were measured for trophic relationships and energy flow in the northern Bering Sea in 2006 and 2007. Lipid content impacts on stable isotope analyses were reduced using a mathematical normalization technique using C/N ratios. Values of del13C in fish species showed significantly different between seasons. Trophic levels (TL) were estimated by del15N values of fish and prey species with primary consumer as a baseline indicator. Bivalves and amphipods had the lowest TL values, 2.4 – 3.4, followed by polychaetes (TL = 3.6 – 4.1), and fish (TL = 3.5 – 4.6).

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List of Abbreviations

AW	Anadyr Water
ACW	Alaska Coastal Water
BSW	Bering Shelf Water
BW	Bottom Water
HLY	*Healy*
NSEDC	Norton Sound Economic Development Corporation
OM	*Oshoro-Maru*
SLI	St. Lawrence Island
SLIP	St. Lawrence Island Polynya
USCGC	U.S. Coast Guard Cutter

Chapter 1

Introduction

1.1 Introduction

The Bering Sea is one of the most productive areas in the sub-Arctic, as well as in the world ocean. The Bering Sea provides 47% of the U.S.A. fishery production by biomass, and is also home to 80% of the U.S.A seabird populations including several endangered species, 95% of northern fur seals, and major populations of Steller sea lions (*Eumetopias jubatus*), walrus, and whales (Overland & Stabeno 2004).

Water from the North Pacific Ocean, rich in nutrients, flows northward over the shallow continental shelf (30 – 70 m), through the Bering Strait, and into the Chukchi Sea and Arctic Ocean. Three main water masses develop in the northern Bering Sea during the ice-free season with high salinity (>32.5) and high nutrient Anadyr Water (AW) on the western side, low salinity (<31.8) and low nutrient Alaska Coastal Water (ACW) on the eastern side, and intermediate salinity (31.8 – 32.5) Bering Shelf Water (BSW) between AW and ACW all flowing northward (Grebmeier et al. 1988, Grebmeier et al. 2006a, Fig.1-1). The high nutrient Anadyr Water, which provides 95% of the northward input of NO_3^-, supports a continuous source of nutrients for high primary production in the water column on the west side of the shelf from the Gulf of Anadyr to north of Bering Strait (300 g C m^{-2} yr^{-1}), and also is the major forcing function for high production in the region south of St. Lawrence Island (SLI) by high nutrient flows west to east

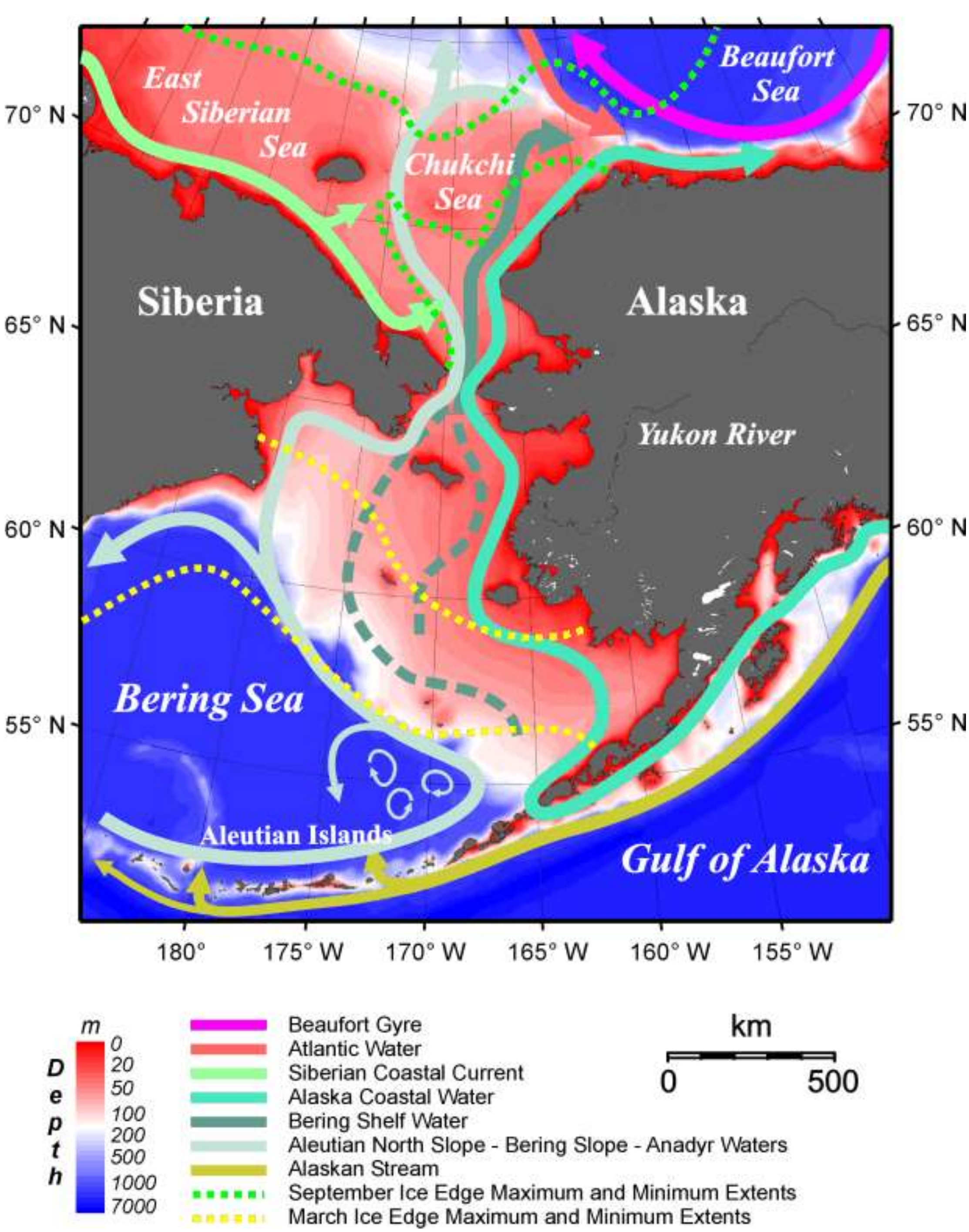


Fig. 1-1. Schematic of water masses from the Bering Sea into the Arctic Ocean (from Grebmeier et al 2006a).

(Walsh et al. 1989, Nihoul et al. 1993, Grebmeier & Cooper 1995, Clement et al. 2005, Grebmeier et al. 2006a).

Generally, from November to May the central and northern Bering Sea is covered with sea ice, which has tremendous influence on, and also plays a significant role in the functioning of the sub-Arctic ecosystem. For example, sea ice provides a resting site for marine mammals, and extensive ice-associated blooms in the spring which support birds and fish (Bluhm & Gradinger 2008). The migration routes of many species of seabirds and mammals follow the ice edge during spring (Ainley & DeMaster 1990). These studies showed that prey availability at the marginal ice zone supports the migration of seabirds. Ice-algae from the under-ice surface develop blooms during ice retreat in April and May (Alexander & Niebauer 1981, Hunt et al. 2002), which support early season growth for pelagic grazers (Tremblay et al. 1989, Conover & Siferd 1993). In addition, there is a delay of maximum zooplankton growth until higher sea water temperatures occur later in the season, thus algae from ice algal production may not be efficiently transferred to the pelagic food web, but tend to pass directly to benthic communities (Legendre et al. 1992, Overland & Stabeno 2004). Ice algal cells, when released from the melting ice in a relatively shallow environment, tend to sink quickly, and the sinking rates were estimated to be 30-60 m/d, meaning cells could reach the benthos in 1-2 days (Grebmeier & Barry 1991). Alternatively, when the spring bloom (open-water bloom) occurs in May or June in warmer water temperatures, coupling between zooplankton and phytoplankton is relatively strong and zooplankton abundance and production is much higher than under cold spring conditions (Coyle & Pinchuk 2002, Hunt et al. 2002). Although zooplankton remain in the euphotic zone when the temperature is warm, the shallow depth enhances the probability of significant carbon export reaching the sea floor and ultimately facilitating the high productivity of the northern Bering Sea benthos in the spring (Grebmeier et al. 2006a, Grebmeier & Barry 2007).

The Bering Sea is undergoing a northward biogeographical shift as a result of atmospheric and hydrographic forcing (Overland & Stabeno 2004, Grebmeier et al. 2006b). Walleye pollock were distributed further north during the years with warmer sea surface temperature (Helle et al. 2007). Climate change in the both the Bering Sea and regions of the Arctic have been dramatic, and the most obvious aspect has been the reduced extent and earlier melting of seasonal pack ice (Grebmeier et al. 2006b). Increases in ocean and atmosphere temperatures and low sea-ice concentration and duration strongly affect the Arctic biological community, with redistributions of marine mammals, shifts in primary productivity, and with visible increases in pelagic fish and birds, and these changes may affect the functioning of food webs (Grebmeier et al. 2006b). In the northern Bering Sea, the characteristic of tight pelagic-benthic coupling of organic production may well be shifting to a more pelagic dominant ecosystem (Grebmeier et al. 2006b).

1.2 Groundfish in the northern Bering Sea

The northern Bering Sea is a region of high water column production with tight coupling with benthic production (Grebmeier & Dunton 2000). High benthic production on the shallow Bering Sea shelf supports a large component of bottom feeding mammals and sea ducks (Welch et al. 1992). In winter, sea ice is formed in the polynya (ice-free area within ice-covered seas) south of SLI and transported to the south of SLI by northerly winds when the polynya is open, and significant heat is lost during the process of ice formation ("latent heat polynya", Morales Maqueda et al. 2004). During ice formation, brine is also rejected and sinks to the bottom to form cold, saline-dense water (Schumacher 1983, Danielson et al. 2006). When winter sea ice melts on the north-central Bering Sea shelf, nearly-freezing bottom water remains even in summer, with temperatures below 0°C, thus limiting the abundance and growth of groundfish (Grebmeier et al. 2006b). This bottom water temperature (BWT) determines the primary boundary for the sub-Arctic and Arctic that affects ecosystem variability (Grebmeier et al. 2006b). Demersal fish and predatory invertebrates are limited by low BWT, however, benthic-feeding seabirds, such as spectacled eiders (*Somateria fischeri*) and marine mammals, including walruses (*Odobenus rosmarus*) and gray whales (*Eschrichtius robustus*) are the key predators in the northern Bering Sea. With a northward biogeographic shift, these organisms may well be undergoing replacement by fish and epi-benthic invertebrate predators (Wyllie-Echeverria & Wooster 1998, Grebmeier et al. 2006b). Fish also move northward to respond to increases in sea water temperature in other areas (Perry et al. 2005).

Thus, it is important to understand the present status of fish communities in the northern Bering Sea, and what environmental factors make the most influence on fish distribution in order to evaluate and ultimately predict possible ecosystem change for management purposes.

1.3 Predator-prey relationship

Interannual and decadal variability in air temperatures, water temperatures, and sea ice extent can influence fish distribution and abundance, and as a result, it can also change predator-prey relationships (Springer et al. 1996). For example, during both cold and warm conditions, predation pressure on age-1 walleye pollock (*Theragra chalcogramma*) has varied with different suites of predators (Wyllie-Echeverria & Ohtani 1999). Expansion of competing fish predators to the northern Bering Sea as ice cover declines and the "cold pool" contracts may affect food availability for other predators, and also impact commercial and subsistence harvests in the sub-Arctic seas. Studies in the northern Bering Sea have found that prey for benthic-feeding mammals and sea ducks have declined, possibly related to changing hydrographic conditions and primary productivity caused by reduced ice extent south of SLI (Grebmeier & Cooper 1995, Grebmeier & Dunton 2000, Grebmeier et al. 2006b). Arctic cod (*Boreogadus saida*) is the most abundant fish species in the northern Bering Sea and Arctic Ocean (Lowry & Frost 1981, see Ch. 2). They are a key species to link zooplankton to higher trophic levels, such as other fishes, birds, and mammals, in marine food webs in this region (Lowry & Frost 1981, Craig et al. 1982). The distribution of Arctic cod is influenced by sea ice (Bradstreet et al. 1986, Gradinger & Bluhm 2004, Bluhm & Gradinger 2008), and the decline in sea ice will likely affect fish abundance and distribution, as well as predators that consume Arctic cod.

Diet composition and food web structure have been investigated by analyzing fish gut contents and stable isotopes. Although stomach content analysis is the traditional and direct approach in food web studies, it has its drawbacks. For instance, it only considers prey that are not digested or assimilated by the predator.

Stable isotope analysis can be used for food web analysis since the stable isotope abundances of carbon and nitrogen in an animal are determined in part by the isotopic abundances in the animal's food and thus reflect diet (Fry & Sherr 1984, Michener & Schell 1994). Based on this approach, stable isotope ratios have been used to estimate the relative trophic level status of important demersal fish species and their prey, as well as overall food web structure. The ratios of $^{13}C/^{12}C$ or $^{15}N/^{14}N$ are expressed as delta value (δ), $\delta^{13}C$ or $\delta^{15}N$, which are measured as parts per thousand (‰) differences between samples and a standard reference material according to the following formula: $x = (R_{sample} - R_{standard})/R_{standard} * 1000‰$, Where x is either ^{13}C or ^{15}N, R is the ratio of carbon ($^{13}C/^{12}C$) or nitrogen ($^{15}N/^{14}N$).

Studies have found that there is an approximate 1‰ enrichment in $\delta^{13}C$ between trophic levels (McConnaughey & McRoy 1979, Hobson & Welch 1992, Rau et al. 1983, Post 2002). Possible reasons for this enrichment are preferential loss of isotopically light $^{12}CO_2$ during respiration, preferential uptake of ^{13}C during digestion, or metabolic fractionation during synthesis of different tissue types (reviewed by Michener & Schell 1994). $\delta^{13}C$ values can be used to identify isotopically different food sources, such as C3 vs. C4 plants, marine vs. terrestrial carbon, or ice-algae vs. pelagic phytoplankton (DeNiro & Epstein 1978, Hobson & Welch 1992, reviewed by Michener & Schell 1994). By comparison, $\delta^{15}N$ has been shown to be more sensitive to trophic fractionation than ^{13}C, and has a stepwise enrichment of 3-4‰ at each trophic level (Hobson & Welch 1992, Post 2002). The enrichment of $\delta^{15}N$ relative to the diet is due to the preferential excretion of heavy ^{15}N in the form of urea and ammonia (Minagawa & Wada 1984). Hence, a dual-isotope approach using $\delta^{13}C$ and $\delta^{15}N$ can be helpful and applicable to answer difficult questions in the food web studies (Post 2002). In this research, the two stable isotope tracers, $\delta^{13}C$ and $\delta^{15}N$ were used to improve understanding of the food web structure in the northern Bering Sea. This methodology, coincident with stomach content analyses, strengthens the evaluation of the food web structure.

1.4 Data Collection

The main field collection was accomplished on two cruises of the USCGC *Healy*, one in spring 2006 (HLY0601) and the other in 2007 (HLY0702) in the northern Bering Sea around St. Lawrence Island (SLI) (Fig. 1-2). Groundfish samples were collected by otter (4.3 m long, 1.9 cm stretched mesh, opening 3.43 m wide) and beam (4.3 m long, 1.9 cm stretched mesh, opening 4 m wide) trawls (Fig. 1-3). Additional fish samples for stable isotope analysis were provided by the Norton Sound Economic Development Corporation (NSEDC) in summer 2006 from a cruise on the R/V *Pandalus* (NSEDC06), and a sample collection from the Japanese T/S *Oshoro-Maru* research cruise in summer 2007 (OM07) (Fig. 1-2).

1.5 Study Objectives

This research is a part of ongoing time series studies in the SLIP region in the northern Bering Sea, specifically during 2006 and 2007, to evaluate the impact of reduced sea ice extent on ecosystem structure in this region. The goal of this study is to assess the possible trends of groundfish communities in the northern Bering Sea and their potential impacts on the food web structure. The main questions are

- What is the groundfish community composition and distribution in the northern Bering Sea, and which environmental habitat characteristics impact the fish distribution most?
- Are there seasonal and spatial differences in fish feeding habitat in the northern Bering Sea, and does competition for prey species between dominant fish species occur? and

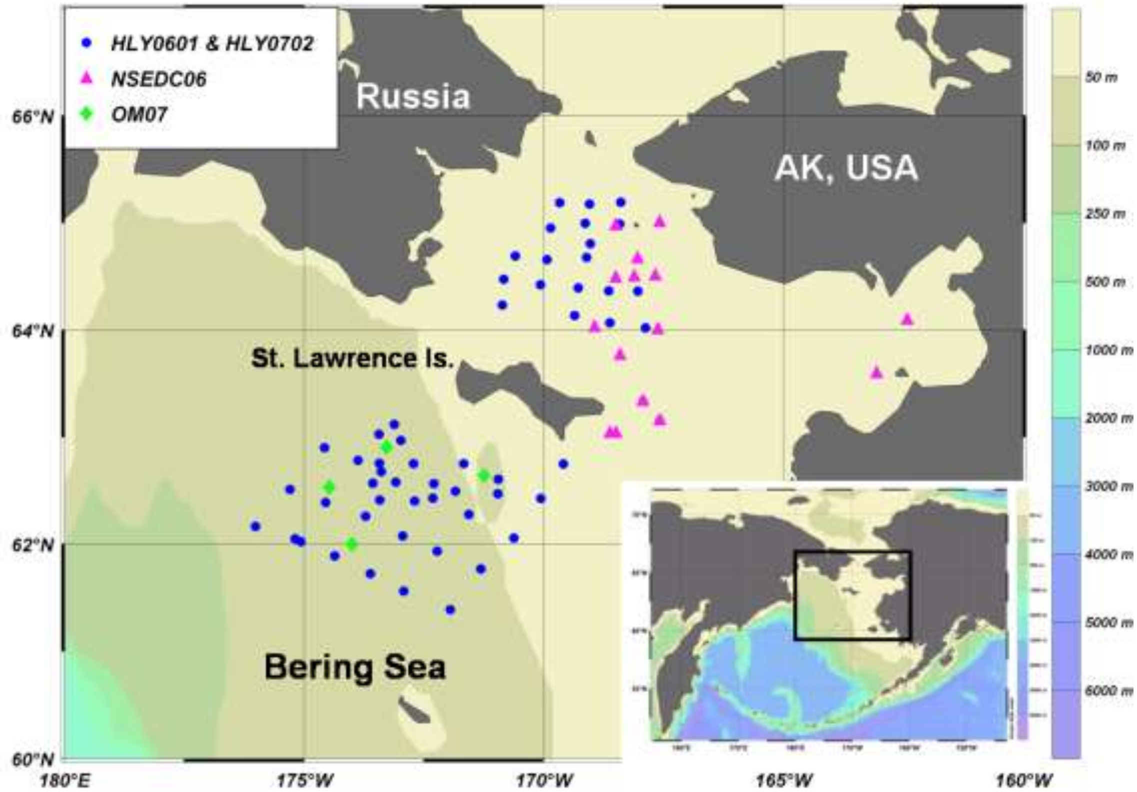


Fig. 1-2. Map of study area and sampling stations in the northern Bering Sea. Circle: HLY0601 & HLY0702; Triangle: NSEDC06; Diamond: OM07.

Fig. 1-3. Photo images of otter (above) and beam (bottom) trawls.

- How does energy flow from lower trophic prey organisms to higher trophic fish predators?

To address these questions, the key objectives of this doctoral dissertation include:

1) To investigate the groundfish distribution and abundance, and their relationships to environmental habitat characteristics using multivariate methods.

2) To determine predator-prey relationships and feeding ecology of groundfish in the study area using stomach content analyses.

3) To analyze trophic levels and food web structure of groundfish and their potential prey items using stable carbon and nitrogen isotopes analyses.

Chapter 2

Spatial distributions of groundfish in the northern Bering Sea in relation to environmental variation

This chapter is a paper submitted for publication by Xuehua Cui, Jacqueline M. Grebmeier, Lee W. Cooper, James R. Lovvorn, Christopher A. North, William L. Seaver and Jason M. Kolts, and it is in revision in Marine Ecology Progress Series. My use of "we" in this chapter refers to my co-authors and myself. My contributions to this paper include sampling groundfish, measuring fish samples, analyzing data, and preparation of the manuscript, apart from the materials and methods for trawl distance measurement prepared by Christopher A. North.

2.1 Introduction

The Bering Sea shelf is one of the most biologically productive regions in the sub-Arctic seas and it supports large populations of fishes, crabs, marine mammals, and seabirds (Loughlin et al. 1999). In particular, the southeastern Bering Sea supports extensive commercial fisheries (Aydin & Mueter 2007). In the northern Bering Sea, the nutrient rich Anadyr Water moves along the western side of the northern shelf through the Gulf of Anadyr, and provides a continuous source of nutrients for high primary production in the western regions of the northern Bering and Chukchi Seas (Springer et al. 1996, Grebmeier & Barry 2007). High nutrient water also moves northward from the southern Bering Sea shelf during the winter onto the northern shelf until seasonal water masses form in the spring (Danielson et al. 2006). Notably a branch of the Anadyr current flows west to east south of St. Lawrence Island (SLI) during the ice-free summer (Walsh et al. 1989, Nihoul et al. 1993, Grebmeier & Cooper 1995, Clement et al. 2005, Danielson et al. 2006, Grebmeier & Barry 2007). Summer primary production is limited in the region after nutrient depletion from the spring bloom.

Evidence is accumulating that the Bering Sea is undergoing a northward biogeographical shift as a result of atmospheric and hydrographic forcing that may be climate-related (Overland & Stabeno 2004, Grebmeier et al. 2006b, Bluhm & Gradinger 2008, Mueter & Litzow 2008). Environmental change over the last decade in the Arctic has been dramatic, and the most obvious evidence has been the reduced extent and earlier melting of seasonal pack ice (Serreze et al. 2007). Increases in ocean and atmosphere temperatures and lower sea-ice concentrations and duration strongly affect Arctic biological communities (Grebmeier et al. 2006b). Near-freezing (< 0 °C) bottom water south of SLI in summer (a "cold pool" resulting from winter sea ice production) limits the numbers and growth of groundfish (Wyllie-Echeverria & Wooster 1998, Grebmeier et al. 2006b). Expansion of fish populations as seasonal sea ice cover declines and the cold pool shrinks may affect food availability for other apex predators, and also impact commercial and subsistence harvests in the sub-Arctic (Grebmeier et al. 2006b). Despite these potentially important ecological changes, the spatial distribution of benthic fish communities and how they are affected by the physical environment are not well-known in the northern Bering Sea. Many past fisheries research programs have focused on single species that are commercially important rather than multi-species communities, and even community-level studies have been undertaken primarily in the southeastern Bering Sea or Gulf of Alaska where commercial fisheries are most prominent (e.g. Brodeur et al. 1999, Mueter & Norcross 2002, Aydin & Mueter 2007, Mueter & Litzow 2008). Therefore, in order to anticipate fish distribution shifts with changing climate and thereby aid management planning for the Bering Sea, a better understanding is needed of benthic fish communities on the northern shelf.

Within this context, the goals of our study were to (1) describe the spatial pattern of demersal fish communities in the northern Bering Sea, and (2) identify the main environmental factors influencing groundfish communities using multivariate approaches.

2.2 Materials and methods

Fish sampling. We sampled groundfish in the northern Bering Sea around SLI (Fig. 2-1) during two cruises on the USCGC *Healy* from 7 May to 5 June 2006 (HLY0601), and 16 May to 18 June 2007 (HLY0702). In 2006, we sampled groundfish using an otter trawl (4.3 m long, 1.9 cm stretched mesh, opening 3.43 m wide) at 43 stations (60 hauls). In 2007, a beam trawl (4.3 m long, 1.9 cm stretched mesh, opening 4 m wide) was used at 52 stations (63 hauls), with replicate otter trawls undertaken at 14 stations to allow comparison of the catch efficiency of the two different sampling nets. All trawls were deployed at a speed of ~2 knots for durations on the bottom of 5 to 30 min in 2006 and 2 to 25 min in 2007. The shorter time durations were used in muddy sediments with very high abundances of brittle stars that otherwise would overwhelm the net in a few minutes. These considerations were used in adjusting trawl bottom time according to expected trawl load, and based on previous trawling efforts (JM Grebmeier, unpublished data).

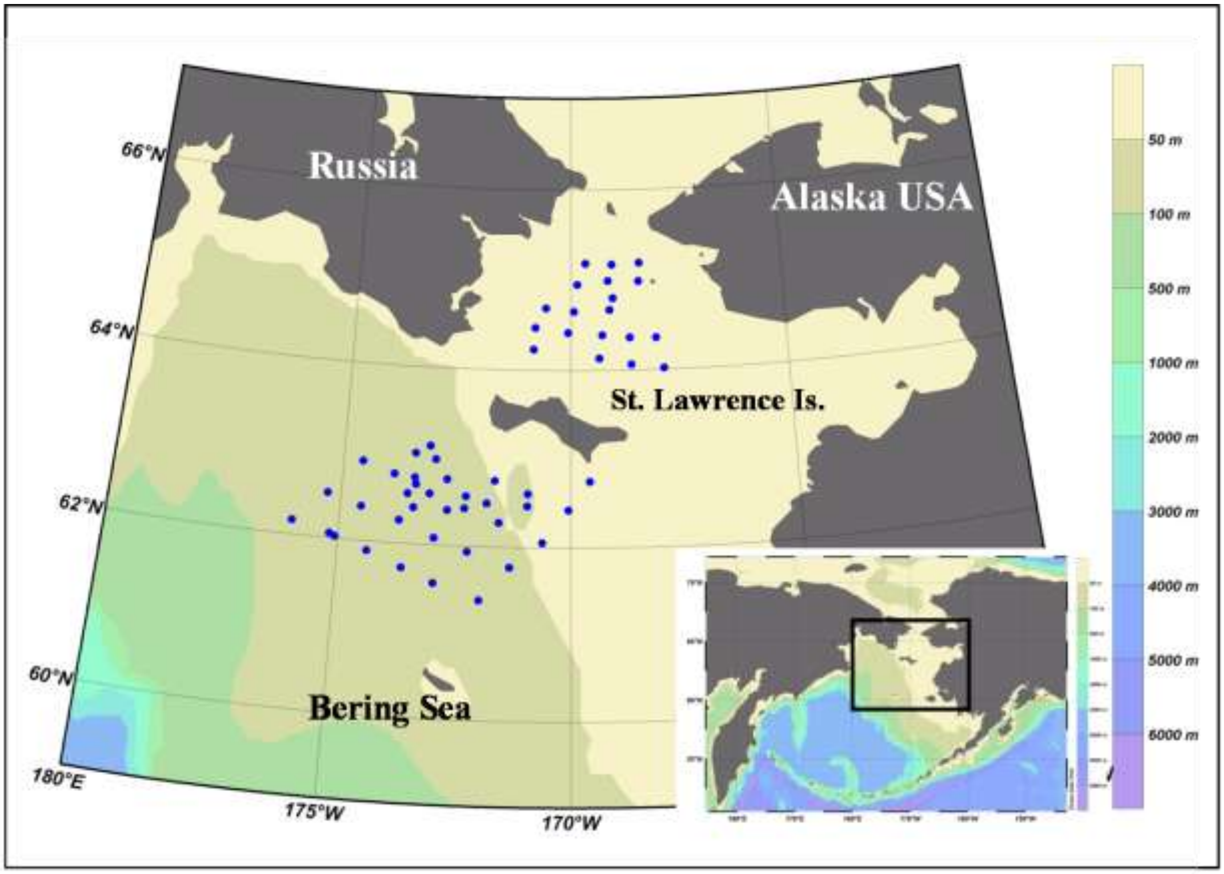


Fig. 2-1. Map of study area in the northern Bering Sea and station locations in 2006 and 2007.

In order to test for possible biases associated with short trawls, six stations were sampled in 2007 with trawl bottom times <5 min were re-sampled with longer bottom times of 5–24 min. No obvious differences in fish communities were detected between samples of differing trawl duration at the same stations.

Fish were sorted and identified to species or to the lowest possible taxon using the keys of Mecklenburg et al. (2002). All fish were measured for total length (TL, ±1 mm), and total mass (TM, ±1 g).

Data standardization. Frequency of occurrence (FO) was calculated for each taxon, indicating the probability of capturing a given taxon in a sampling area. The catch per unit area (CPUA) of each species was expressed as both number of fish km^{-2} and kg of fish km^{-2}. Area swept by the net was computed as the effective width of the net opening (otter trawl = 3.43 m, beam trawl = 4 m) multiplied by the distance towed on the bottom. In 2007, distances towed on the bottom were calculated for the beam and otter trawls by means of a shipboard global positioning system (GPS) and a trawl-mounted depth logger (Sensus Ultra, ReefNet Inc., Mississauga, Ontario, Canada) that allowed us to determine the precise period the trawls were on the bottom. In 2006, when depth loggers were not deployed, we estimated the trawling time on the bottom using regression analyses of the relationship between cable payout length, depth, and heading from the 2007 data sets when depth loggers were deployed, and then calculated distance traveled over the estimated time period using shipboard GPS data. All bottom trawl distances were corrected for trawl movement relative to ship movement by means of electronically recorded winch data. Specifically, we employed a correction formula with the length of payout cable (m) when the net first reached the bottom set equal to (2.073 × depth) + 11.2 for stations south of SLI, and (2.420 × depth) – (0.272 × southing) + 22.1 for stations north of SLI, where southing = |heading – 180°| (CA North, unpublished data).

To examine changes in CPUA for abundance and biomass in the two years, we used regression models to convert otter trawl CPUA in 2006 to comparable beam trawl CPUA with 14 station replicates. For CPUA in terms of fish abundance, two stations weight = 0.00 (VNG4) and 0.25 (SEC2) were treated as an outlier and partial outlier, with the remaining 12 stations having weight from 0.77 to 1.00 by Andrew's sine robust linear regression model by Number Cruncher Statistical System software (NCSS 2007, Hintze 2009; see Fig. 2-2a). The resulting relationship between beam (B) and otter (O) trawls was B = –74.77 + 0.202 × O (r^2 = 0.85). For CPUA in terms of biomass, one outlier (station RUSA) was eliminated. The relationship was best described by a nonlinear regression B = 0.0068 × O + 0.000163 × O^2 (r^2 = 0.92) (Fig. 2-2b). In both outlier stations VNG4 and RUSA, trawl time was 2-3 min, which might have caused the variance in the sampling results. We used these regressions to convert otter trawl data in 2006 to equivalent beam trawl data. The regression model for fish abundance is more reliable than the model for fish biomass because the data are more evenly distributed across the range of values. However, in beam trawl data from 2007, fish assemblages identified in terms of abundance showed no large differences from those identified in terms of biomass.

Environmental data. Fourteen environmental variables were measured at each trawl station, including (1) depth (m), (2) bottom water temperature (ºC), (3) bottom water salinity, (4) bottom water silicate (µmol L^{-1}), (5) bottom water nitrite and nitrate (µmol L^{-1}), (6) bottom water phosphate (µmol L^{-1}), (7) bottom water ammonium (µmol L^{-1}), (8) bottom water chlorophyll *a* (mg m^{-3}), (9) integrated water column chlorophyll *a* (mg m^{-2}), (10) chlorophyll *a* in surface

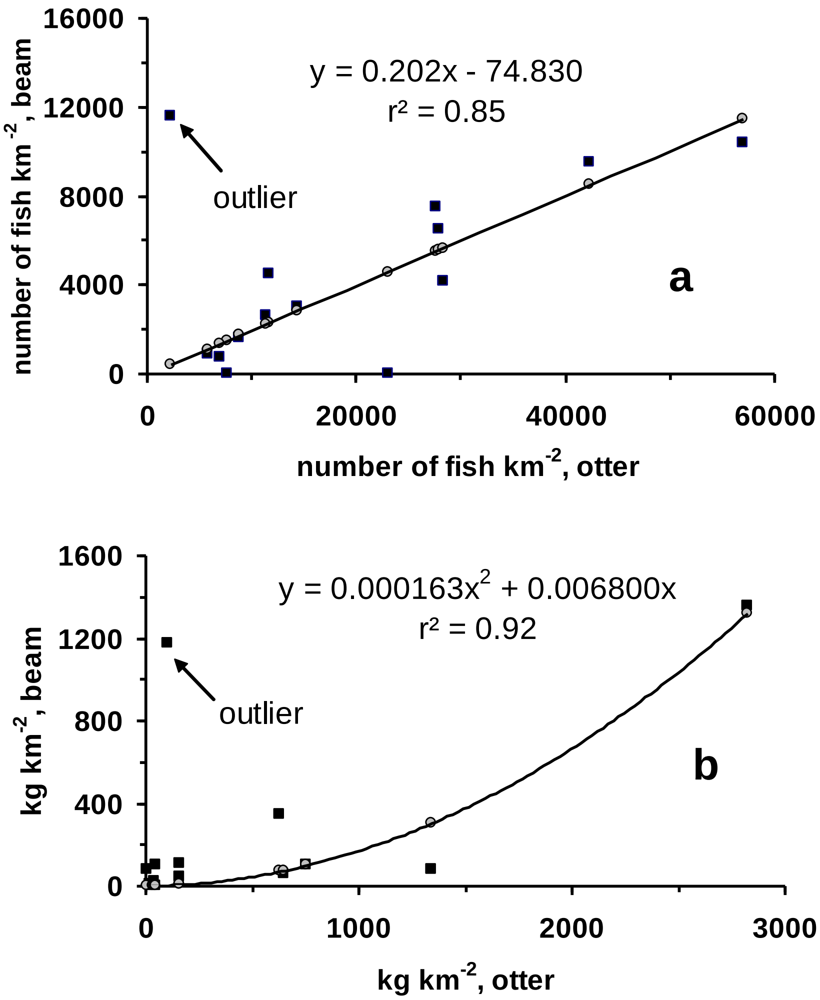


Fig. 2-2. Graph showing the observed (black rectangle) and predicted (gray circle) values of abundance (a) and biomass (b) CPUA, based upon regression analysis used to facilitate comparisons between the two trawl methods (see text). CPUA = catch per unit area.

sediments (mg m^{-2}), (11) surface sediment grain size (phi), (12) total organic carbon of surface sediments (TOC, %), (13) total organic nitrogen of surface sediments (TON, %), and (14) surface sediments C/N (wt/wt). Bottom water was collected from 0 to 5 m above the bottom.

The 14 hydrographic and sediment parameters were measured as follows. Depth, temperature, and salinity were measured by sensors mounted on a conductivity-temperature-depth (CTD) profiler. Water samples for inorganic nutrients (items 4–7 above) were collected from the rosette of bottles on the CTD. These samples were frozen upon collection and analyzed at the Marine Science Institute at the University of California, Santa Barbara, using a nutrient autoanalyzer. For chlorophyll determinations, additional seawater samples (250 ml) were collected at up to 12 depths from the same rosette, filtered using Whatman GF/F filters, and extracted in 90% acetone for 24 h at 4 ºC in the dark. At the end of this incubation period, chlorophyll *a* concentrations in the water column were measured with a Turner Designs AU-10 fluorometer without acidification (see Cooper et al. 2002 and Clement et al. 2004 for detailed methods). For measurements of sediment chlorophyll *a*, duplicate 1-cm^3 samples of surface sediments were collected from the top of a van Veen grab at each station. After adding 10 ml of 90% acetone to each sediment sample, samples were stored for 12 h at 4 ºC in the dark, and the chlorophyll *a* concentration was measured using the same fluorometer (Cooper et al. 2002, Clement et al. 2004). Samples for sediment grain size and total organic carbon and nitrogen in sediments were collected from the top centimeter of HAPS benthic cores collected at each station (Grebmeier et al. 1989). Sediment subsamples (1 g) were acidified with 2 ml of 1 N HCl and dried at 105 ºC overnight before measurements of TOC and TON were made on a CHN analyzer (Exeter Analytical model 240XA). Samples for sediment grain size were dried, homogenized, chemically processed to remove organics, and sieved using standard geological sieves (0 to 4 phi mesh size). Sediments were weighed after sieving and percent composition and modal sediment size calculated (see Pirtle-Levy 2006 for further details).

Fish community and habitat relationships. Cluster analysis and multidimensional scaling (MDS) were used to distinguish groundfish assemblages and spatial distributions. These methods were conducted with the statistical software PRIMER (v6, Plymouth Routines in Ecological Research, Plymouth, UK; http://www.primer-e.com). Reoccupied stations in each year were treated as independent samples. A few fish species that occurred at fewer than 5% of stations were excluded from cluster analysis (following Gauch 1982, Clarke & Warwick 2001). We grouped fish species and stations according to fish abundance, and used hierarchical clustering with group-average linking of Bray-Curtis similarities on log(x+1) transformed benthic fish abundance data (Clarke & Warwick 2001). Log-transformation was used to reduce the influence of dominant species. The dominant fish species and environmental factors in cluster groups were compared for significant differences using a two-sample Hotelling's T2 randomization test based on 10,000 Monte Carlo samples by means of NCSS 2007 software (Number Cruncher Statistical System; Hintze 2009). Randomization test is conducted by enumerating all possible permutations of the sample data, calculating the statistic test for each permutation, and counting the number of permutations with a T2 value equal or greater than the actual T2 value (Hintze 2009). Dividing this count by the number of permutations tried gives the significance level of the test (Hintze 2009). This two-sample Hotelling's T2 test is a multivariate version of Student's t-test, and randomization does not rely on assumptions such as equal variance and normal distribution (Hintze 2009).

The BIO-ENV procedure in PRIMER was used to link environmental variables to fish community structure, including estimates of how well environmental characteristics explained fish distributions. This procedure handles separately biotic and abiotic data; constructs sample (dis)similarity matrices, such as Bray-Curtis for biota and Euclidean distance for abiotic variables, and chooses an abiotic variable subset to maximize rank correlation (ρ) between biotic and abiotic (dis)similarity matrices (Clarke & Warwick 2001). Log-transformed data log(x+1) were used for all biotic and abiotic variables (Clarke & Warwick 2001). In other words, rank was compared through the Spearman coefficient (ρ), which has the range (–1, 1), with the extremes of ρ = –1 and +1 corresponding to cases where the two sets of ranks are in complete opposition or complete agreement.

2.3 Results

Environmental conditions in trawl survey stations. During sampling in May and June, ice cover was lower in 2007 than in 2006 (Fig. 2-3). The depth range of trawl deployments was 35 to 96 m. Bottom water temperatures at most trawl survey stations were from –1.8 to –1.4 °C south of SLI in both 2006 and 2007, reflecting the presence of a cold pool generated by ice formation in the winter polynya south of SLI (Fig. 2-4a). Warmer bottom water temperatures occurred north of SLI, particularly in 2007 (–0.4 to 0.6 °C). Mean bottom water salinity (± SD) was higher in 2007 (32.7 ± 0.2) than in 2006 (32.1 ± 0.3) (Fig. 2-4b). Integrated water column chlorophyll *a*

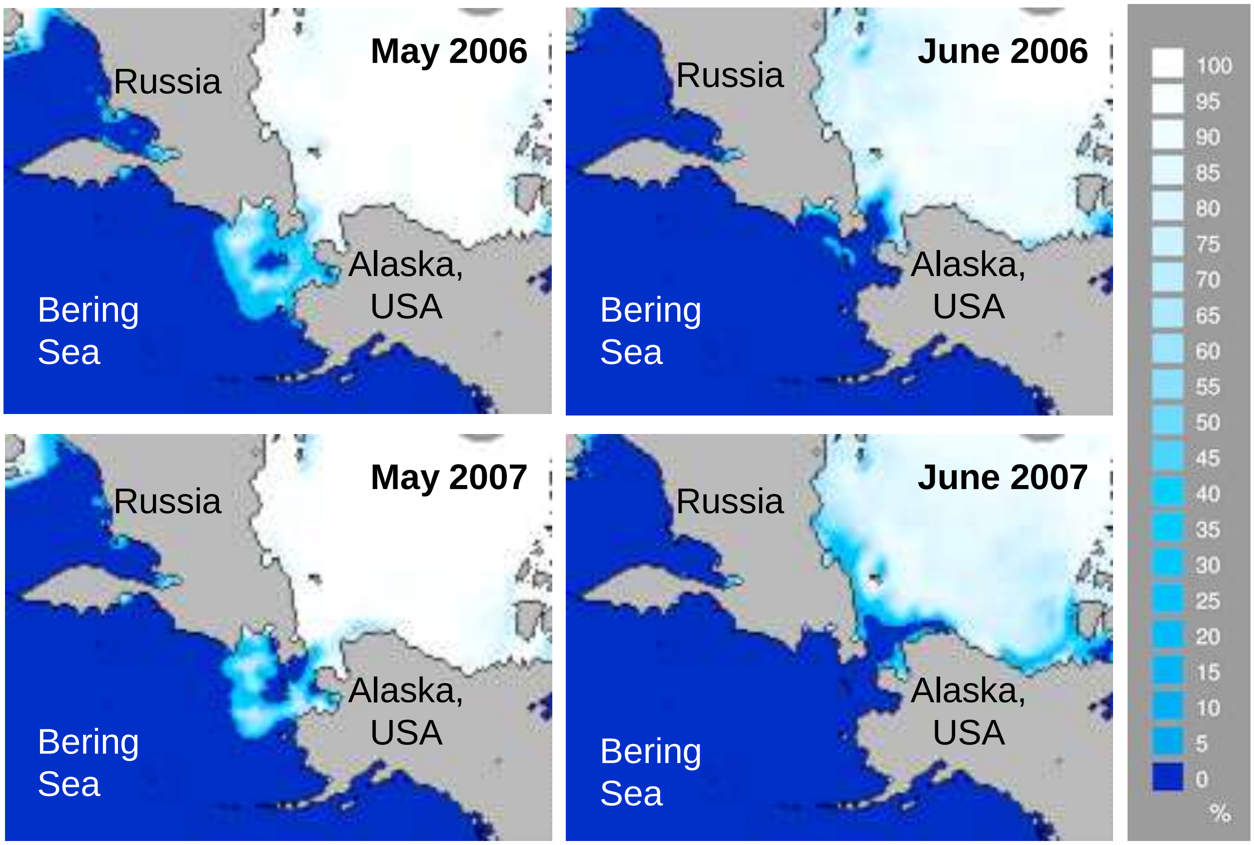
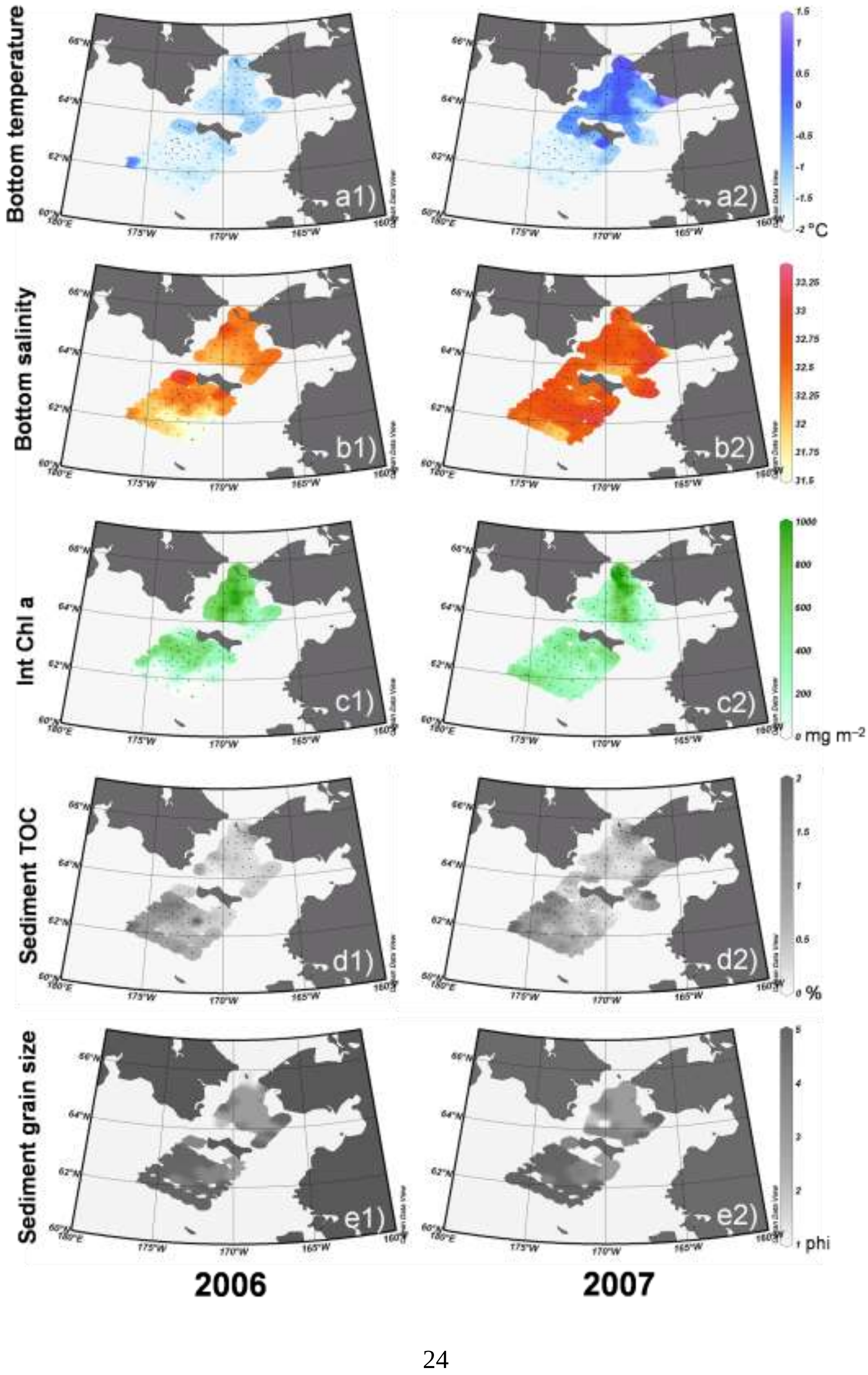


Fig. 2-3. Sea ice concentration in May and June 2006 and 2007 (images edited from the Sea Ice Index (Fetterer et al. 2008)).

Fig. 2-4. Spatial pattern of selected environmental factors in 2006 (left) and 2007 (right) sampling seasons. Bottom temperature = bottom water temperature (°C), Bottom salinity = bottom water salinity, Int Chl *a* = integrated water column chlorophyll *a* (mg m^{-2}), Sediment TOC = total organic carbon in surface sediments (%), Sediment grain size = surface sediment grain size (phi).


Bottom temperature
Bottom salinity
Int Chl a
Sediment TOC
Sediment grain size
a1)
a2)
b1)
b2)
c1)
c2)
d1)
d2)
e1)
e2)
°C
mg m−2
%
phi
2006
2007

was lower (10 to 100 mg m^{-2}) in 2006 at stations to the southeast and farthest south of SLI, and higher (300 to 800 mg m^{-2}) in most of the remaining stations (Fig. 2-4c). In 2007, the highest chlorophyll *a* concentrations integrated over the water column (700 to 1000 mg m^{-2}) were observed from northeast of SLI extending toward the Bering Strait, with lower concentrations (100 to 500 mg m^{-2}) observed elsewhere. Organic matter in surface sediments (TOC and TON) was highest to the southwest of SLI in both years (Fig. 2-4d). Sediment grain size, an indicator of current speed, generally was finer south of SLI and coarser north of SLI, with gravel close to the Bering Strait (Fig. 2-4e).

Comparison of otter and beam trawls. Differences in the sizes of fish caught by the two different gear types were tested in 2007 at fourteen stations where both trawls were deployed (Table 2-1). Mean lengths (± SD) of fish differed significantly ($p = 0.0001$) between the otter (95 ± 63 mm) and beam trawls (144 ± 87 mm) by Hotelling's T2 randomization test. Depending on species, the otter trawl often caught a higher proportion of small fish than any caught by the beam trawl (Fig. 2-5). We speculate that as the catch accumulated in the otter trawl, the head rope would become lower and the doors and foot rope would dig deeper into the sediments, perhaps selecting against larger fish and for smaller benthic fish compared to the beam trawl, which has a higher and more constant mouth opening and runners instead of doors. For instance, the total length of shorthorn sculpins (*Myoxocephalus scorpius*) caught by the otter trawl averaged (±SD) 222 ± 103 mm (range 52 to 335 mm), while those caught by the beam trawl averaged 301 ± 46 mm (range 230 to 380 mm) (Table 2-1).

Perhaps because of this apparent tendency of the otter trawl to catch larger numbers of smaller fish, abundances of the four dominant fish species were 2.2 to 4.6 times higher in samples from

Table 2-1. Mean dominant fish abundance and their ratios as collected by otter and beam trawls, along with the mean length of fish collected during 2007 using both devices at 14 stations. Numbers in parentheses are sample size

Common name	Scientific name	Abundance (# fish km^{-2}) Beam (mean ± SD)	Abundance (# fish km^{-2}) Otter (mean ± SD)	otter/beam ratio	Length (mm) Beam (mean ± SD)	Length (mm) Otter (mean ± SD)
Arctic cod	*Boreogadus saida*	148 ± 600	2748 ± 2381	18.6	182 ± 0 (1)	90 ± 30 (50)
Bering flounder	*Hippoglossoides robustus*	1173 ± 1762	2636 ± 3172	2.2	123 ± 43 (13)	79 ± 59 (54)
Snailfish	Liparidae	1288 ± 2562	4738 ± 7655	3.7	89 ± 27 (15)	79 ± 16 (74)
Arctic alligatorfish	*Ulcina olrikii*	113 ± 457	1589 ± 2255	14.1	71 ± 0 (1)	60 ± 8 (19)
Arctic staghorn sculpin	*Gymnocanthus tricuspis*	688 ± 1875	1857 ± 4952	2.7	98 ±17 (6)	87 ± 18 (15)
Shorthorn sculpin	*Myoxocephalus scorpius*	428 ± 1332	1980 ± 4084	4.6	301 ± 46 (10)	222 ± 103 (26)

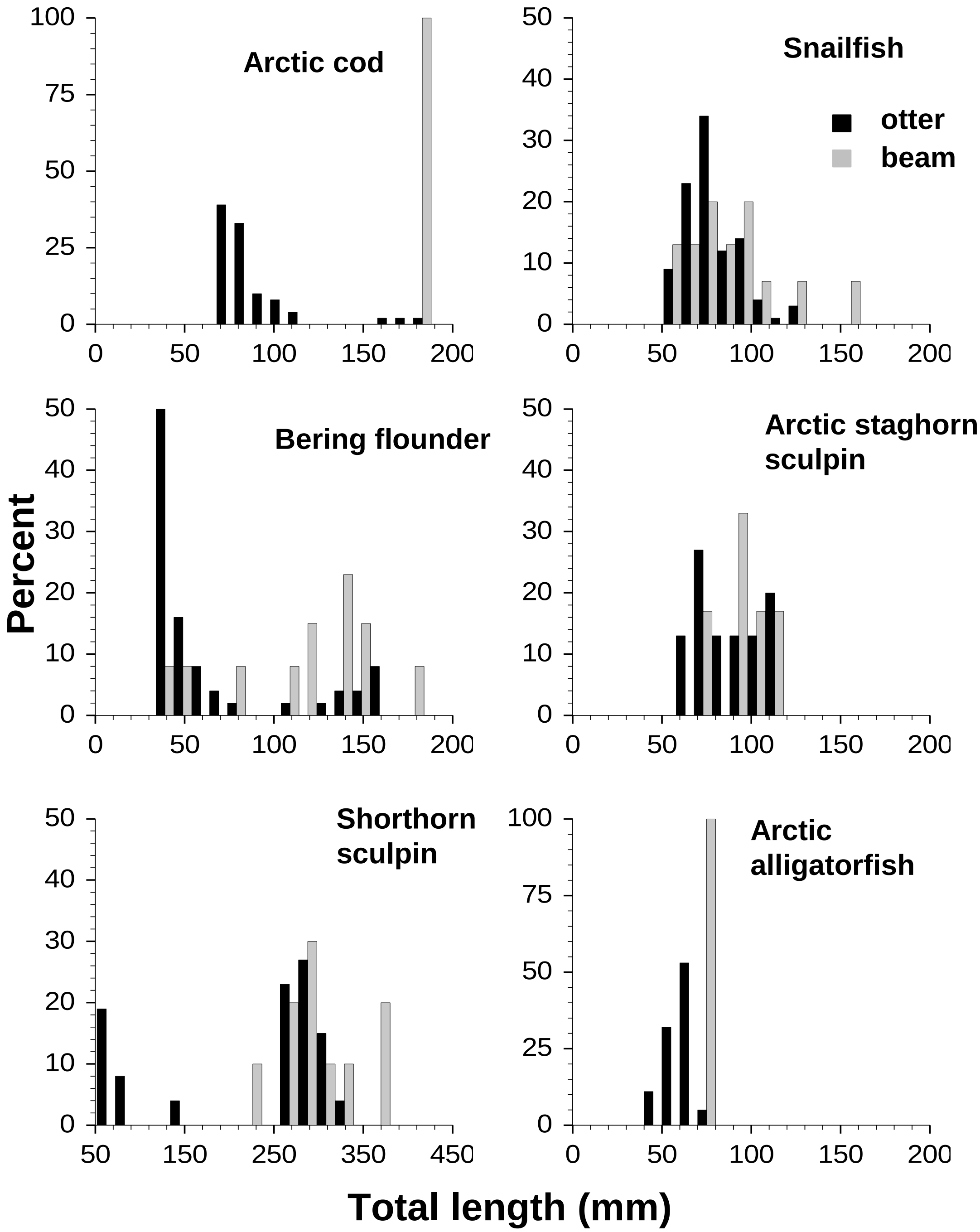


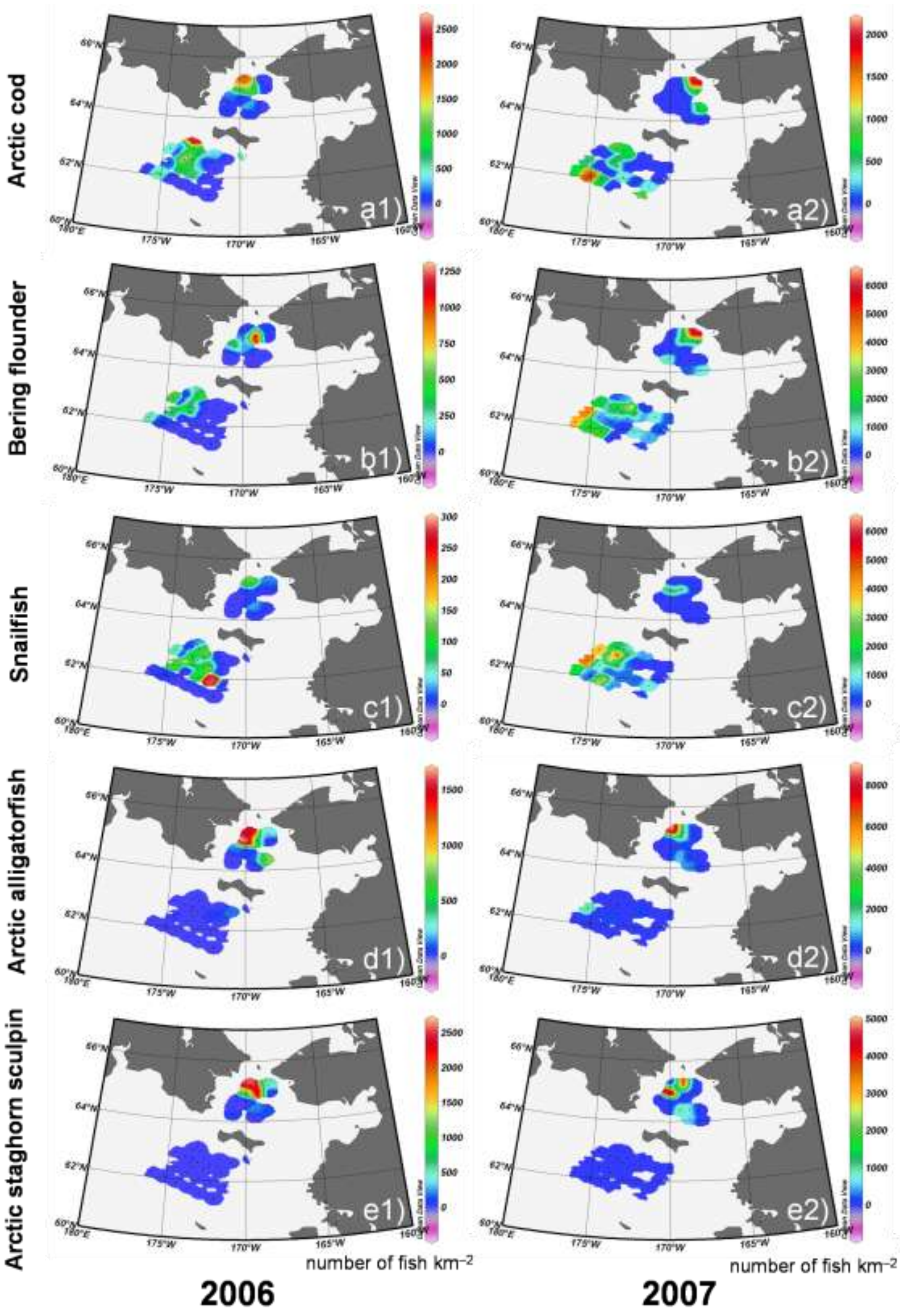
Fig. 2-5. Histograms of the main fish species caught by beam (gray) and otter (black) trawls in 2007.

the otter trawl than from the beam trawl (Table 2-1). Ratios of abundance in the otter trawl vs. the beam trawl were 18.6 for Arctic cod (*Boreogadus saida*) and 14.1 for Arctic alligatorfish (*Ulcina olrikii*). These extreme differences were amplified because these species were caught at only one of 14 stations by the beam trawl, resulting in low mean values in beam trawl abundance (see Table 2-1). Accordingly, we found that a greater number of fish were caught by the otter trawl than beam trawl at the same stations in 2007.

Groundfish spatial distribution. In 2006 we collected 1034 fish representing at least 26 species [snailfish (Liparidae) were identified only to family level in both years], and 973 fish representing at least 17 species in 2007. A few unidentified species were also collected each year. When the otter trawl was used in 2006, most stations (82%) had 2 to 6 species, no station had more than 8 species, and three stations (5%) had no catch of fish. When the beam trawl was used in 2007, no station had more than 6 species, and 9 stations (14%) had no catch of fish. In 2006, almost half of the stations had >1000 fish km^{-2} (Fig. 2-6). In 2007, 75% of the stations had fish abundance >1000 fish km^{-2}, and about one third of the stations had >5000 fish km^{-2}, including one station (DLN4) that had >20,000 fish km^{-2} (Fig. 2-6). Fish species caught in the study area were small in size (<220 mm, except flatfish) compared with commercial fishery observations in the southern Bering Sea; the largest fish caught in both years were shorthorn sculpin (up to 430 mm) (Fig. 2-7).

Arctic cod, Bering flounder (*Hippoglossoides robustus*), and snailfish generally had high abundance and high frequency of occurrence (FO > 50%) among stations in both years except that Arctic cod were caught at only 32% of stations in 2007 (see Table 2-2). Arctic cod had the highest abundance of all fish in 2006 with FO of 75%, whereas Bering flounder had the highest

Fig. 2-6. Spatial patterns of dominant demersal fish by abundance in 2006 (left) and 2007 (right). Cold color (blue) represents fish abundance equal to or close to zero, warm color (red) is the highest value. Scales on right are number of fish km^{-2}.


Arctic cod
Bering flounder
Snailfish
Arctic alligatorfish
Arctic staghorn sculpin
a1)
a2)
b1)
b2)
c1)
c2)
d1)
d2)
e1)
e2)
number of fish km−2
number of fish km−2
2006
2007

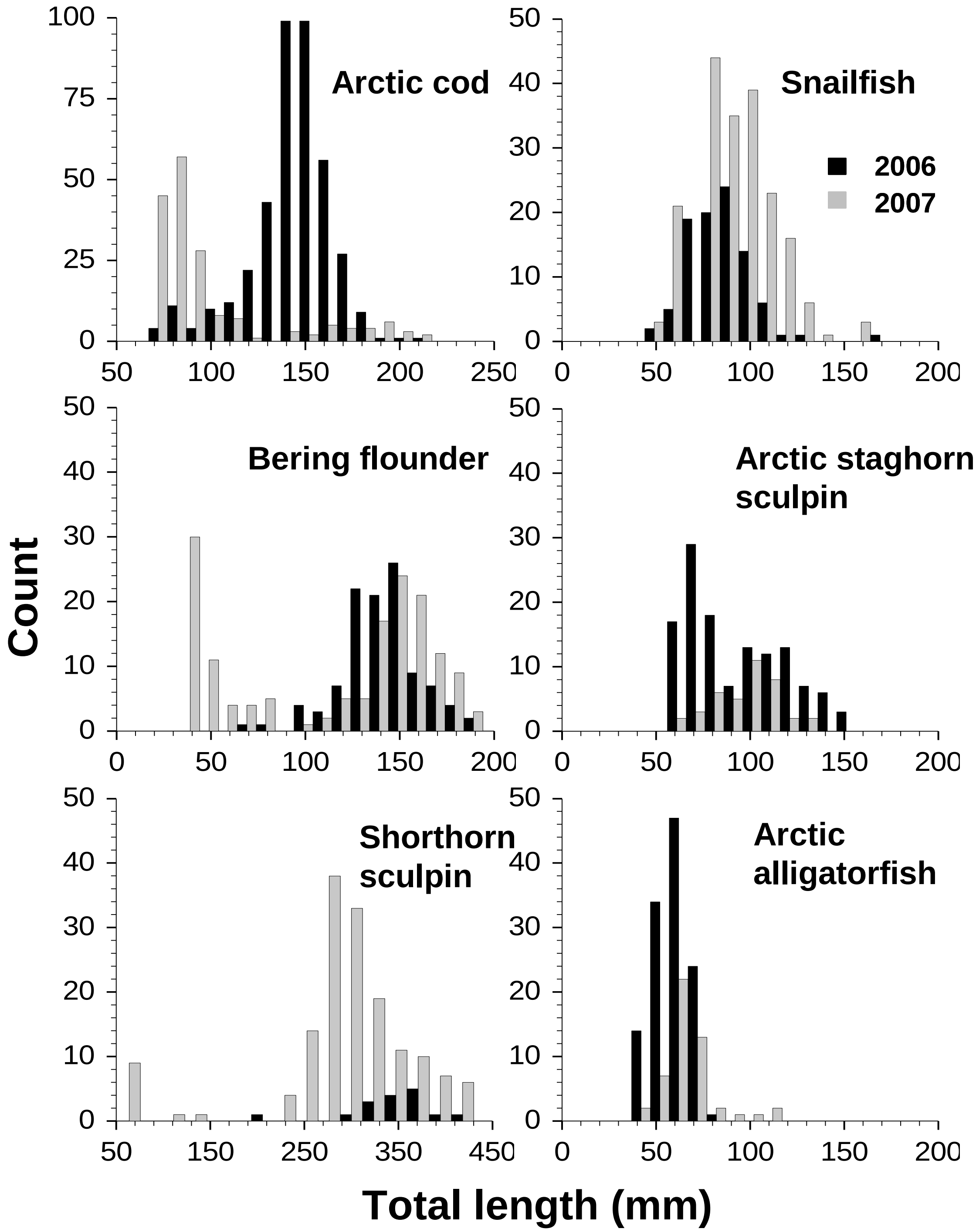


Fig. 2-7. Total length of dominant fish species from all catches in 2006 (black) and 2007 (gray).

Table 2-2. Groundfish frequency of occurrence (FO) and their mean abundance CPUA in 2006 and 2007. Mean abundance from original otter trawl data in 2006 were adjusted to be comparable to data from the beam trawl in 2007 (Fig. 2-2a). Species are only tabulated when FO was higher than 3% in any one year

		2006		2007	
Common name	**Scientific name**	**FO (%)***	**Abundance (# fish km^{-2})**	**FO (%)***	**Abundance (# fish km^{-2})**
Arctic cod	*Boreogadus saida*	75	509	32	316
Bering Flounder	*Hippoglossoides robustus*	56	146	75	1207
Snailfish	Liparidae	56	52	51	1061
Walleye Pollock	*Theragra chalcogramma*	42	34	3	14
Arctic alligatorfish	*Ulcina olrikii*	27	88	13	289
Arctic staghorn sculpin	*Gymnocanthus tricuspis*	17	118	8	189
Veteran poacher	*Podothecus veternus*	15	4	8	67
Stout eelblenny	*Anisarchus medius*	10	12	5	25
Shorthorn sculpin	*Myoxocephalus scorpius*	8	8	11	463
Yellowfin sole	*Limanda aspera*	8	1	5	31
Capelin	*Mallotus villosus*	8	2	-	-

Table 2-2. Continued

Common name	Scientific name	2006 FO (%)*	2006 Abundance (# fish km^{-2})	2007 FO (%)*	2007 Abundance (# fish km^{-2})
Alligatorfish	*Aspidophoroides monopterygius*	8	1	2	10
Pacific herring	*Clupea pallasii*	5	3	2	5
Sakhalin sole	*Limanda sakhalinensis*	3	0	3	14
Wattled eelpout	*Lycodes palearis*	2	4	5	73
Alaska plaice	*Pleuronectes quadrituberculatus*	10	0	3	19
Pacific cod	*Gadus macrocephalus*	-	-	3	10
Spatulate sculpin	*Icelus spatula*	-	-	3	6

*FO: Frequency of Occurrence.

abundance in 2007 with FO of 75%. Shorthorn sculpin had the highest biomass in both years with low FO (8 – 11%). Most fish species had higher abundance and biomass in 2007 than 2006 (Table 2-2).

In both sampling years, there were consistently two species groups (I & II) and two distinctive station groups (we term South & North, out of three station groups identified) determined from fish abundance data (Fig. 2-8a, b). Arctic cod, Bering flounder, and snailfish were in a distinct species group I and Arctic alligatorfish and Arctic staghorn sculpin (*Gymnocanthus tricuspis*) clustered in a species group II. The stations sharing similar fish community structure were grouped into clusters and a third overlapping group we term O (Overlap). The South cluster was the largest and located mainly to the southwest and at a few stations north of SLI. This cluster group was typified by co-occurring species group I, including Arctic cod, Bering flounder, and snailfish. In 2006, Arctic cod was most abundant, and the latter two species were most abundant in 2007. Station group North was located north of the island and was dominated by species group II, Arctic alligatorfish and Arctic staghorn sculpin, and also high numbers of Arctic cod in 2006. In 2007, Shorthorn sculpin occurred for the most part in the North group. Station group O overlapped spatially with station group South, and was dominated by high numbers of snailfish in 2006, and Arctic cod and snailfish in 2007. Hotelling's T2 randomization test showed a significant difference ($p < 0.01$) between station group South and North in some fish species, but no significant difference ($p > 0.05$) either South or North with O in either year. Arctic staghorn sculpin and Arctic alligatorfish were significantly (both $p < 0.001$) higher in abundance in station groups North than in South in 2006, and shorthorn sculpin was significantly ($p < 0.001$) higher in 2007.

Fig. 2-8. (a) 2006, (b) 2007; (1) Dendrogram separating three groups (A, B, C) by cluster analysis based on fish abundance in each year: (2) MDS (multidimensional scaling) diagram; (3) spatial distribution and abundance of the main fish species of station groups using cluster analysis of fish abundance. Data from the otter trawl in 2006 were adjusted to be comparable to data from the beam trawl in 2007 (Fig. 2-2) (Group South, circles filled with black to gray; Group North, green filled triangles; Group O, blue filled triangles; outlier group, cross). AC = Arctic cod, BF = Bering flounder, SN = snailfish, AA = Arctic alligatorfish, ASS = Arctic staghorn sculpin, WP = walleye pollock, SS = shorthorn sculpin, WE = wattled eelpout.

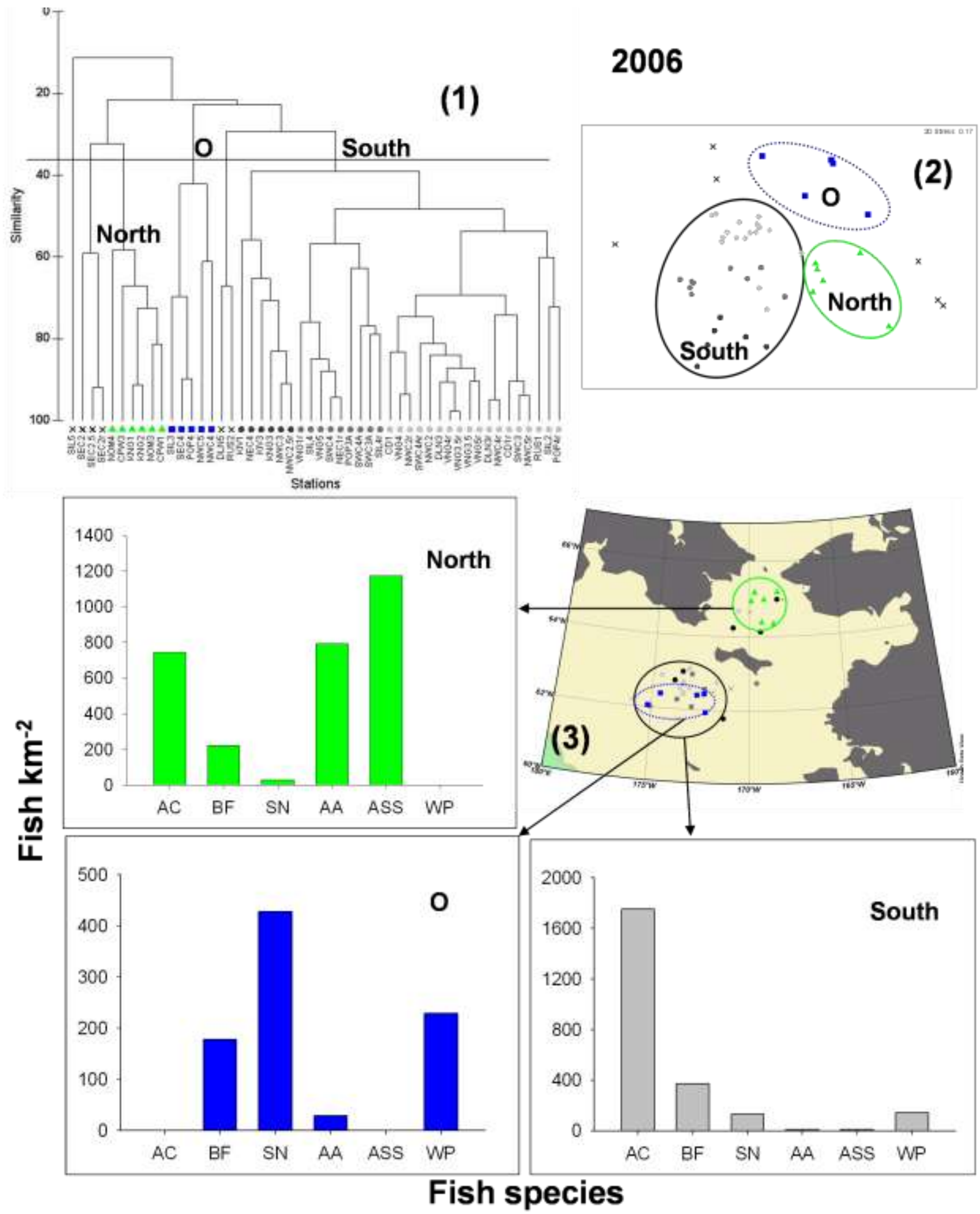
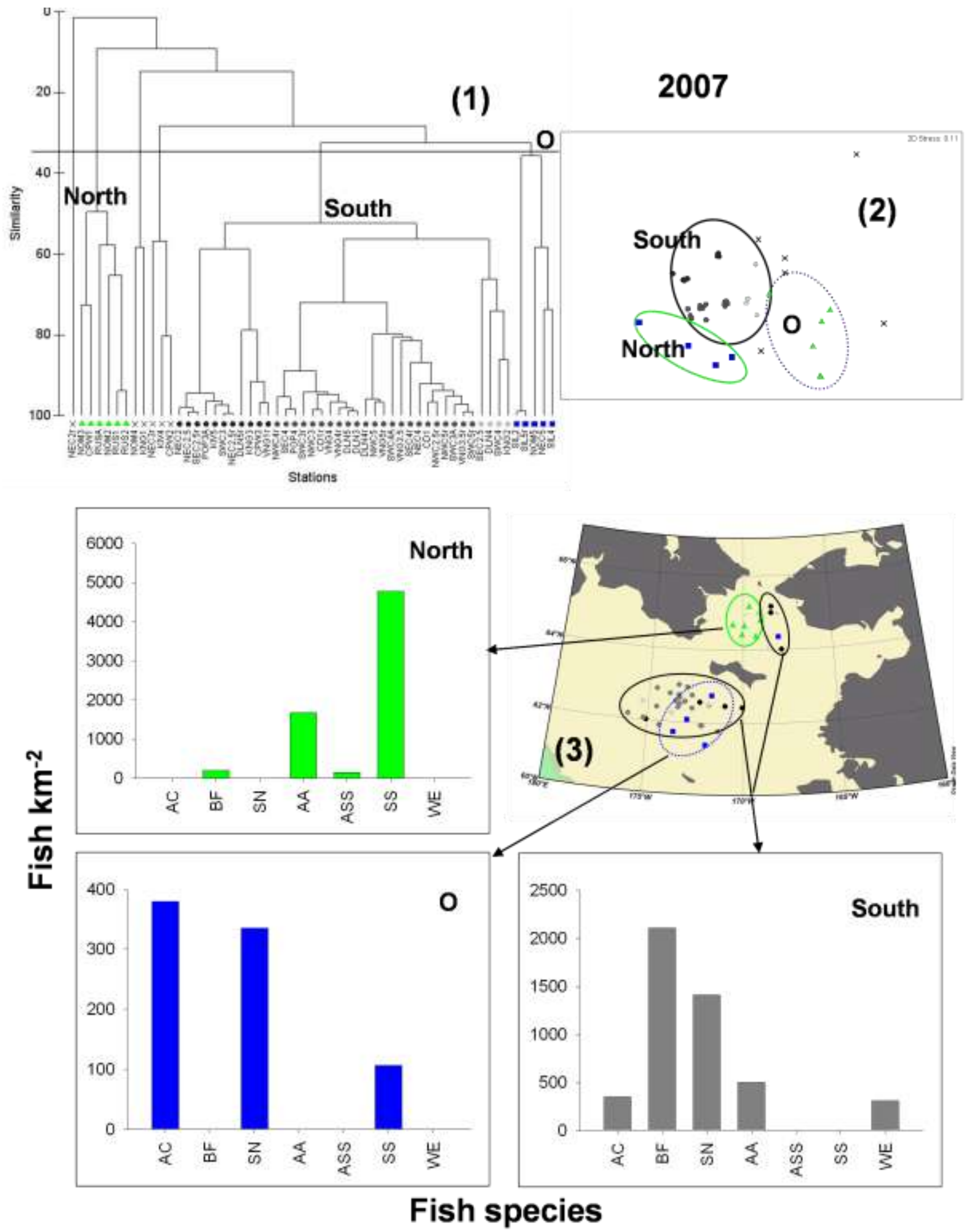

2006
(1)
(2)
(3)
North
O
South
Similarity
Stations
Fish km-2
Fish species
AC
BF
SN
AA
ASS
WP

Fig. 2-8a



2007
(1)
(2)
(3)
North
South
O
Similarity
Stations
Fish km-2
Fish species
AC
BF
SN
AA
ASS
SS
WE

Fig. 2-8b

Relationship with environmental factors. The randomization procedure of Hotelling's T2 test revealed that environmental variables were not significantly different between station group South and O ($p > 0.05$), whereas environmental variables were significantly different between station group South and North ($p = 0.02$ in 2006, $p = 0.001$ in 2007). Station group South had lower bottom water temperatures, was deeper, had lower bottom water and integrated water column chlorophyll *a* values, finer sediment grain sizes, and higher sediment total organic carbon and nitrogen content than group North ($p < 0.01$, Table 2-3).

The BIO-ENV procedure indicated that there were high correlations ($\rho > 0.95$, collinearity) between silicate and phosphate and between TOC and TON in 2006. Therefore, we excluded some parameters where they were co-linear because of confounding effects on the analysis (Clarke & Warwick 2001). On this basis we retained silicate and TOC in the analysis structure and phosphate and TON were dropped from the BIO-ENV procedure in 2006. The result showed that 4-variable subsets had better correlations ($\rho = 0.46$ & 0.45) than any other best single abiotic variable or 2- and 3-way variable combinations in 2006 (Table 2-4). Adding additional variables above these four only marginally improved correlations in 2006. We concluded that the four optimal parameters in 2006 were bottom water nitrate + nitrite, bottom water chlorophyll *a* (or integrated water column chlorophyll *a*), sediment grain size and sediment C/N, which were best correlated with fish distributions in 2006. In 2007 the correlation ($\rho = 0.51$) was slightly better for a best 2-variable combination (bottom water temperature and sediment grain size) than for the best single abiotic variable (bottom water temperature, $\rho = 0.50$) with little correlative improvement with addition of third and higher variables (Table 2-4). Therefore, bottom water

Table 2-3. Dominant fish species (+) and absent fish species (–) in each group, and significant environmental factors ($p < 0.01$) influencing fish abundance. n = sample size in each group, T = bottom water (BW) temperature, BW Chl *a* = BW chlorophyll *a*, Int Chl *a* = integrated water column chlorophyll *a*, Grain size = sediment grain size, TOC = total organic carbon in surface sediments, TON = total organic nitrogen in surface sediments

Year	**2006**		**2007**	
Station group	**South (n=30)**	**North (n=6)**	**South (n=38)**	**North (n=6)**
Fish species				
Arctic cod	+	+	+	–
Bering flounder	+	–[a]	+	–[a]
Snailfish	+	–[a]	+	–
Arctic alligatorfish	–[a]	+	–[a]	+
Arctic staghorn sculpin	–	+	–	–[a]
Shorthorn sculpin	–[a]	–	–	+
Environmental factors*	**(mean ± SD)**			
T (˚C)	-1.6 ± 0.2	-1.4 ± 0.2	-1.4 ± 0.6	-0.0 ± 0.4
Depth (m)	64 ± 12	45 ± 4	65 ± 14	45 ± 3
BW Chl *a* (mg m^{-3})	6.5 ± 4.5	18.0 ± 5.1	-	-
Int Chl *a* (mg m^{-2})	465 ± 216	780 ± 160	-	-
Grain Size (phi)	4.7 ± 0.6	3.2 ± 0.4	4.6 ± 0.7	3.3 ± 0.5
TOC (%)	1.0 ± 0.5	0.3 ± 0.1	1.0 ± 0.5	0.4 ± 0.2
TON (%)	0.2 ± 0.1	0.1 ± 0.0	0.2 ± 0.1	0.1 ± 0.0

* included environmental factors having significant difference ($p<0.01$) between groups, except TON in 2007 having significant difference ($p < 0.05$). Non significant ($p>0.05$) values were omitted. Significant test was performed using Hotelling's T2 randomization test;

[a] fish occurred in only a few stations.

Table 2-4. The combination of environmental variables that best explains groundfish community structure in 2006 and 2007. Up to two options with highest Spearman correlation with $p < 0.01$ (null hypothesis: $\rho = 0$) in each number of variables are shown, and no more than 5 variables are included. T = Bottom water (BW) temperature, Si = BW Silicate, N = BW Nitrite + Nitrate, NH_4 = BW Ammonium, BW Chl *a* = BW chlorophyll *a*, Int Chl *a* = Integrated water column chlorophyll *a*, Grain size = Sediment grain size, TOC = Surface sediment total organic carbon, C/N = Surface sediment total organic carbon and nitrogen ratio; optimal combinations are in bold and italic

#	2006	ρ§	2007	ρ§
1	Grain size;	0.290	***T;***	***0.496***
			Grain size	0.400
2	Int Chl *a*, Grain size;	0.365	***T, Grain size;***	***0.508***
	Int Chl *a*, TOC	0.364	T, Si	0.470
3	Int Chl *a*, Grain size, C/N;	0.420	T, Si, Grain size;	0.509
	BW Chl *a*, Grain size, C/N	0.417	T, NH_4, Grain size	0.492
4	***N, BW Chl a, Grain size, C/N;***	***0.457***	T, Si, Grain size, TOC;	0.503
	N, Int Chl a, Grain size, C/N	***0.447***	T, Si, NH_4, Grain size	0.499
5	Depth, N, BW Chl *a*, Grain size, C/N;	0.468	T, Si, NH_4, Grain size, TOC;	0.496
	Depth, N, Int Chl *a*, Grain size, C/N	0.459	T, Si, N, BW Chl *a*, Grain size	0.494

§ Spearman correlation.

temperature and sediment grain size were identified as the environmental variables that best explained fish distribution in 2007.

2.4 Discussion

Water mass and fish abundance. The results indicate two distinct spatial distributions of benthic fish communities in the northern Bering Sea. One group, located south of St. Lawrence Island (SLI), was dominated by Arctic cod, Bering flounder, and snailfish. Another group, located north of SLI, was dominated by Arctic alligatorfish and Arctic staghorn sculpin or shorthorn sculpin. Bottom water temperatures were lower south of SLI and higher north of SLI. Coincidently, sediment grain size was characterized by finer silt/clay sediments south of SLI compared to coarser, sandy sediments north of SLI, indicative of the slower and faster current regimes in the different regions, respectively.

Benthic fish populations south of SLI were more abundant in the western side of the St. Lawrence Island Polynya (SLIP) region where there is a higher proportion of saline, nutrient-rich Anadyr water vs. the eastern side of the SLIP region, which is known to be more influenced by fresher, nutrient-depleted Bering Shelf Water and Alaska Coastal Water in the spring. Another difference is finer grain size sediments on the western side of the southern SLI system compared to relatively more coarse sediments on the eastern side of the study area. Thus, the associated variability in habitat and environmental conditions suggests these different habitats support different benthic fish assemblages, and the variation in fish species distribution is controlled by hydrographic features and sediment type (associated with current speed).

Difference in fish abundance and size structure in the two years. Arctic cod was widely distributed with FO of 75% by otter trawl in 2006, and 32% by beam trawl in 2007, which is consistent with previous work in this area (Lowry & Frost 1981, FO of 56% by otter trawl). Arctic cod had a much lower FO and abundance in 2007 than in 2006, which might be related to lower seasonal ice coverage in 2007 at the time of sampling. The overall distribution of Arctic cod is associated with ice cover, which the fish use for feeding and protection from predators (Andriyashev 1964, Lønne & Gulliksen 1989, Crawford & Jorgenson 1993, Wyllie-Echeverria & Wooster 1998). Similarly, Arctic cod are more abundant in the northeastern Chukchi and western Beaufort Seas where there is more ice cover than in the northern Bering Sea (Lowry & Frost 1981).

We found that beam trawls tend to catch larger fish than otter trawls, however, we collected a higher proportion of small size class Arctic cod, Bering flounder, and shorthorn sculpin by beam trawl in 2007 than in 2006 using an otter trawl (Fig. 2-7). There was no major difference in snailfish length between the two years, while Arctic staghorn sculpin and Arctic alligatorfish had higher proportions of smaller fish in 2006 than in 2007. The small size class peaks in Fig. 2-7 may represent first-year recruits for some species. The mean length we observed for Arctic cod (~80 mm) is similar to other observations in the Bering, Chukchi, and Beaufort Seas (Craig et al. 1982, Lowry & Frost 1981, Gillispie et al. 1997). Previous studies suggest that warmer waters and less ice cover may increase survival and growth of Arctic cod (Gillispie et al. 1997, Fortier et al. 2006). In addition, Arctic cod populations can respond to environmental conditions within a year, while other fish such as walleye pollock respond over time frames of several years (Wyllie-Echeverria & Wooster 1998).

It is possible that warmer temperature and the reduced ice extent in 2007 increased young of the year (YOY) fish abundance in some species. Bering flounder for example move northward with higher bottom water temperature (Mueter & Litzow 2008, Spencer 2008). In our study, Bering flounder was more abundant (from 1200 fish km^{-2} to 6000 fish km^{-2}) close to Bering Strait, where bottom water temperatures were much higher in 2007 relative to 2006. Shorthorn sculpin, which were dominant north of SLI, increased in 2007 coincidently with the higher bottom water temperature in the North station group.

Responses to climate factors vary widely among fish species (Skud 1982). Our results show that the different changes in abundance in fish size groups in the two years are coincident with their general distribution patterns. Generally, Arctic cod, Bering flounder, and shorthorn sculpin are distributed throughout the Bering Sea and into the Arctic Ocean. Snailfish occur only south of Bering Strait with the exception of a few species. Arctic staghorn sculpin and Arctic alligatorfish are distributed from north of SLI to the Arctic Ocean (Mecklenburg 2002, Fig. 2-7). Different thermal tolerances of “arctic” and “subarctic” community groups are likely to lead to differing responses to the increased bottom water temperature (Mueter & Litzow 2008). However, our data do not show clear evidence of a one year response to a shift in temperature. Further work is needed to evaluate whether fish communities respond directly to changing seawater temperatures, or whether the differences observed result only from asynchronous inter-annual variations among species.

Reproductive strategies might also affect the response of fish size structure to climate change. For example, sculpins lay adhesive eggs in nests and many provide parental care for eggs, while other groundfish species do not (Eschmeyer et al. 1983). This reproductive strategy of sculpins might make them more sensitive to changes in benthic habitats than other groundfish species which produce pelagic eggs (Reuter & TenBrink 2008).

Effects of grain size and temperature. We found that sediment grain size had a significant influence on groundfish distributions in both years. Scott (1982) suggested that sediment particle size and water column depth were correlated with groundfish distribution. McConnaughey and Smith (2000) concluded that strong preferences among sediment textures by flatfish results from differences in prey availability. Arctic staghorn sculpin were absent in muddy or clay sediments, and burrowed in sandy-muddy sediments (Andriyashev 1964, Smith et al. 1997). The distributions and abundances of benthic invertebrates in this region are highly correlated with sediment type (Grebmeier et al. 1989, Grebmeier & Barry 2007). Therefore, habitat factor (such as sediment grain size) may directly or indirectly influence fish assemblages.

In 2006 sampling occurred earlier in the season (7 May to 5 June) than in 2007 (16 May to 18 June), and 2006 also had higher sea ice cover which influences the development of the spring bloom. We found that the concentration of chlorophyll *a* in the bottom water (and water column) differed between station groups North and South in 2006, which was likely due to the different timing of the spring bloom and settling of phytoplankton to the benthos between the two areas. In 2007, the main bloom in both regions had progressed further as the ice had retreated earlier and we also arrived ~10 days later than in 2006, thus we observed no difference in chlorophyll *a* concentrations in the bottom water (and water column) between station groups North and South. We suggest that during the colder year (2006), bottom-water (and water-column) chlorophyll *a* might have impacted benthic fish distributions indirectly by affecting the total amount of phytodetritus reaching the benthos, thus influencing the distribution and abundance of benthic prey to fish. In addition, in 2006 there was less of a temperature difference between the southern and northern areas, thus temperature was not a significant variable influencing fish population structure. With the later station occupations in 2007 when ice cover was reduced and bottom seawater warmer to the north of SLI, temperature had greater influence on fish community structure, since the region south of SLI still had cold bottom water temperatures due to the presence of the cold pool.

Reorganization of fish communities can be triggered by climate regime shifts, although other complex factors (such as availability of prey or nutrients) can also be important (Anderson & Piatt 1999, Litzow et al. 2006). In the North Sea, a number of fish species have shifted northward in response to increases in sea temperature (Perry et al. 2005). Similarly, in the Bering Sea, walleye pollock were distributed further north during years with warm sea surface temperatures (SSTs) than in years with cool SSTs (Helle et al. 2007). Our results suggest that groundfish community distribution and abundance are also affected by environmental factors such as bottom water temperature, sediment grain size, and water column nutrients via impacts on primary production. If recently observed warming trends continue in the Bering Sea (e.g. Overland & Stabeno 2004, Grebmeier et al. 2006b), it might change the hydrodynamics and indirectly affect sedimentation (or sediment grain size, Dolch & Hass 2008), which is in turn another influence on groundfish abundance and distribution in the northern Bering Sea. The fish assemblages and their relations to environmental factors identified in this study were based on only two spring seasons and available measurements of 14 environmental factors. Thus our data is limited in the extent that it addresses seasonal changes or longer-term trends among years. In spite of this, our results may provide important information for developing effective ecosystem management and modeling of future fish population change with climate warming.

Chapter 3

Feeding ecology of dominant groundfish in the northern Bering Sea

This chapter is a paper to be submitted soon for publication by Xuehua Cui, Jacqueline M. Grebmeier, and Lee W. Cooper. My use of “we” in this chapter refers to my co-authors and myself. My contributions to this paper include sampling groundfish, sorting fish stomachs, analyzing data, and preparation of manuscript.

3.1 Introduction

The Bering Sea is one of the most productive areas in the sub-Arctic region including commercial fisheries in the southeastern Bering Sea, and it is also an important foraging area for seabirds and mammals (Loughlin et al. 1999, Aydin & Mueter 2007). The Bering Sea is undergoing a northward biogeographical shift that may be climate-related (Overland & Stabeno 2004, Grebmeier et al. 2006, Bluhm & Gradinger 2008), most likely due to increasing seawater temperature (Moss et al. 2009). If this trend continues, commercial fish and sub-Arctic species in the southeastern Bering Sea will continue to expand northward and might affect food availability for top predators, including walrus, bearded seals, belugas, grey whales, and eiders through coincident changes in pelagic ecosystem structure (Tynan & DeMaster 1997, Grebmeier & Dunton 2000, Grebmeier et al. 2006). It is thought that the timing of the spring phytoplankton bloom, which is affected by early ice melting, will support a more pelagic food web instead of providing food to the benthos (Stabeno & Overland 2001). Several studies have found evidence for a decrease in benthic productivity in the northern Bering Sea over the last two decades (e.g. Moore et al. 2003, Grebmeier et al. 2006). Furthermore, reorganization of fish ranges in the Bering Sea could have significant impacts on ecosystems, especially predator-prey relationships when the available food resources change. The distribution of species also reflects the effect of interspecific interactions, so that interactions within the population must be included for the prediction of a species distribution in response to climate change (Davis et al. 1998).

Despite these potential ecological changes and significant ecological linkages, predator-prey relationships in groundfish are largely unknown in the northern Bering Sea. For example, Arctic cod plays a critical role in the ecosystem, particularly as prey for belugas, harp seals, seabirds and other fish (Bradstreet et al. 1986, Welch et al. 1992). The goals of this study were to (1) examine the diet of northern Bering Sea dominant fish communities, (2) identify the common prey and feeding strategies of dominant fish species, and (3) explore the potential competition on food resources among the dominant fish species.

3.2 Materials and methods

Study area. Fish were collected in the northern Bering Sea around St. Lawrence Island (SLI, Fig. 3-1), during two cruises on the USCGC *Healy* from 7 May to 5 June 2006 (HLY0601), and 16 May to 18 June 2007 (HLY0702). We sampled groundfish using otter (4.3 m long, 1.9 cm stretched mesh, opening 3.43 m wide) and beam (4.3 m long, 1.9 cm stretched mesh, opening 4

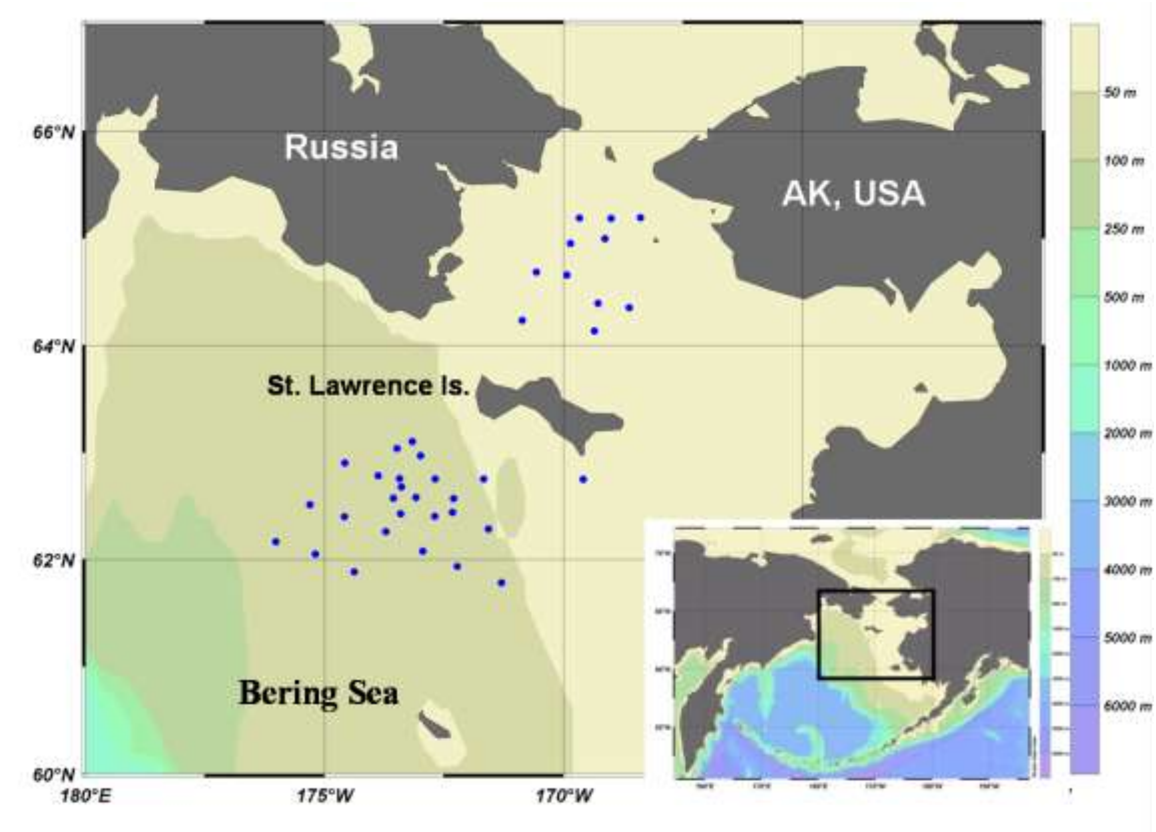


Fig. 3-1. Groundfish sampling locations for stomach content analysis in the northern Bering Sea.

m wide) trawls during the two years (for details see Ch 2; Cui et al. in revision). Depths of the sampled stations ranged from 35 to 96 m.

Diet analysis. Fish samples were sorted and identified to species or to the lowest possible taxonomic level using published keys (Mecklenburg et al. 2002) and measured for total length (TL, ±1 mm). Fish subsamples for stomach content analysis were evenly picked by size. Prey were identified to the lowest possible taxonomic level, which depended on the level of digestion, using a dissecting microscope. In addition, the abundance of each recognizable organism was counted and wet mass of each taxon were obtained to the nearest 0.0001g. For further analysis, prey species were pooled into major prey categories based on taxonomic similarity. The abundances of the different prey items in the diet of the dominant demersal fish species were expressed as a numeric frequency (N_i: percentage of the number of individuals of prey i in relation to the sum of all prey individuals in all the stomachs); frequency of occurrence (F_i: percentage of stomachs which contained a particular prey i); weight frequency (W_i: percentage of weight of prey i in total stomach content weight); and the index of relative importance adjusted to 100% (%IRI = $F_i \times (N_i + W_i)$) (Cortés 1997).

We used the graphical approach of Amundsen et al. (1996) for stomach contents to explore prey importance, feeding strategy and niche width. This method is based on a two-dimensional plot of the prey-specific abundance (P_i, which is the number of individuals of prey i divided by the total number of prey individuals within the stomachs containing prey i) against F_i. Prey that plot in the upper part of the graph are consumed by specialized predators, whereas those located in the lower portion of the plot are consumed on a more general basis (generalization, Amundsen et al. 1996). Prey located in the upper-right of the plot are considered dominant prey and consumed in a greater extent by a specialized predator, reflecting a predator population with a narrow niche width (Amundsen et al. 1996). In contrast, if prey are only located along or below the diagonal from the upper left to the lower right, the predator population is classified as having a broad niche width (Amundsen et al. 1996).

Benthic invertebrate samples were collected in the study area by van Veen grab (0.1 m^2) in 2006. Four replicate samples were taken at each station, and the samples were washed over a 1-mm sieve, preserved in 10% buffered formalin, and later sorted and identified to family level at the lab (see Grebmeier et al. 1988 and Grebmeier & Cooper 1995 for detailed methodology). The grabs were collected to investigate the abundance of benthic invertebrates in relation to the prey collected in the fish stomachs.

Diet overlap (R_o) between size classes and species was evaluated using Schoener's index: $R_o = 1 - \frac{1}{2}\sum |p_{iA} - p_{iB}|$ (Linton et al. 1981), where P_{iA} and P_{iB} are the abundance of prey *i* on the diet of species A and B, respectively. Both N_i and W_i were used to compute this index. The overlap index, R_o, varies between 0 (no overlap) and 1 (complete overlap). Values of this index ≥0.6 have been considered biologically significant in previous studies (Zaret & Rand 1971, Warburton & Blaber 1992, Dolbeth et al. 2008). Although overlap is not a true measure of competition, it is usually the closest approach available to evaluate competition, since direct measurement is not normally available for field studies (Lawlor 1980).

Statistical analyses. Statistical tests were performed with NCSS 2007 software (Number Cruncher Statistical System; Hintze 2009). Chi-square test was used to assess seasonal differences in the diet.

3.3 Results

Dominant fish type and diet composition

Arctic cod (*Boreogadus saida*), Bering flounder (*Hippoglossoides robustus*), snailfish (Liparidae), Arctic staghorn sculpin (*Gymnocanthus tricuspis*), Shorthorn sculpin (*Myoxocephalus scorpius*), and Arctic alligatorfish (*Ulcina olrikii*) were dominant groundfish within the bottom trawl survey. Of the 297 fish stomachs examined, all of Bering flounder were empty in 2006 and 2007. All other fish species contained prey in their stomachs.

Arctic cod: In 2006, the total length (TL) of Arctic cod were 80 – 90 mm (n = 4) and 100 – 220 mm (n = 180). Since there were only four fish in the small size fraction, we considered all individuals as one group. Calanoid copepods were the dominant prey (95.0% N_i, 42.5% W_i, 74.5% F_i, 74.0% IRI), followed by amphipods (1.8% N_i, 42.9% W_i, 76.6% F_i, 24.7% IRI), which were predominantly benthic amphiods and some planktonic hyperiid amphipods (1.3% W_i) (Table 3-1, Fig. 3-2). The most important amphipods were from the benthic family Ampeliscidae (12.5% W_i) found in Arctic cod stomachs. We also compared prey of Arctic cod geographically. We found that Arctic cod (n = 147) from south of SLI preyed mainly on calanoid copepods (57.1% W_i) followed by benthic amphipods (24.7% W_i) and euphausiids (7.3% W_i), while those from north of SLI consumed almost exclusively benthic amphipods (93.0% W_i), which were primarily from the family Ampeliscidae in 2006 (Fig. 3-3).

In 2007, we separated Arctic cod into two groups by size, (TL = 70 – 110 mm, n = 20 and TL = 140 – 220 mm, n = 13). Small Arctic cod mainly consumed calanoid copepods (94.2% N_i,

Table 3-1. Diet composition of Arctic cod, snailfish, and Arctic staghorn sculpin in the northern Bering Sea in 2006. N_i = numeric frequency; W_i = weight frequency; F_i = frequency of occurrence; IRI = proportional index of relative importance

Prey	Arctic cod (n = 184)				Snailfish (n = 44)				Arctic staghorn sculpin (n = 76)			
	%N_i	**%W_i**	**%F_i**	**%IRI**	**%N_i**	**%W_i**	**%F_i**	**%IRI**	**%N_i**	**%W_i**	**%F_i**	**%IRI**
Polychaeta	0.0	1.6	9.8	0.1	4.9	15.0	70.5	7.8	3.5	31.3	27.6	9.5
Ampharetidae									3.1	24.8	9.2	2.5
Polynoidae	0.0	1.6	9.8	0.1	4.4	2.1	22.7	0.8	0.3	1.3	1.3	0.0
Amphipoda	1.8	42.9	76.6	24.7	88.8	75.0	100	91.6	22.0	67.8	100	88.6
Ampeliscidae	1.2	12.5	23.4	2.3	37.4	24.4	59.1	20.4	5.4	51.6	80.3	45.2
Aoridae	0.1	0.3	4.9	0.0	4.4	1.2	13.6	0.4	3.5	3.5	13.2	0.9
Cedicerotidae	0.0	0.0	0.5	0.0								
Hyperiidae	0.1	1.3	6.0	0.1					6.2	0.3	7.9	0.5
Isaeidae	0.0	0.0	1.1	0.0	4.4	0.6	15.9	0.4	2.8	0	3.9	0.1
Ischyroceridae	0.0	0.0	2.2	0.0	15.5	0.6	31.8	2.9	1.0	0.1	3.9	0.0
Lysianassidae	0.0	0.4	2.2	0.0	12.6	16.2	25.0	4.0				
Melitidae	0.1	8.3	7.1	0.4	6.3	10.8	18.2	1.7	0.7	0.3	1.3	0.0
Oedicerotidae	0.1	0.1	4.3	0.0	3.4	0.3	6.8	0.1				
Phoxocephalidae	0.0	0.0	0.5	0.0								
Calanoid copepods	95.0	42.5	74.5	74.0	0.5	0.0	2.3	0.0				
Euphausiids	0.7	6.8	19.0	1.0	0.5	2.4	22.7	0.4	0.0	0.4	1.3	0.0
Decapods (Shrimp)	0.0	1.2	1.6	0.0	1.0	0.2	2.3	0.0				
Mysidae					0.5	0.8	2.3	0.0				
Cumacea	0.1	0.1	10.3	0.0	1.9	0.3	11.3	0.1				
Nuculana radiata	0.0	0.0	0.5	0.0	0.5	0.0	2.3	0.0				
Mollusk siphons									12.8	0.2	14.5	1.9
Ostracods					0.5	0.0	2.3	0.0				
Hermit crabs	0.0	0.1	0.5	0.0								
Fish	0.0	3.3	2.2	0.1	0.5	4.3	2.3	0.1				
Unidentified	0.0	0.5	1.6	0.0	0.5	0.0	2.3	0.0	0.0	0.4	2.6	0.0

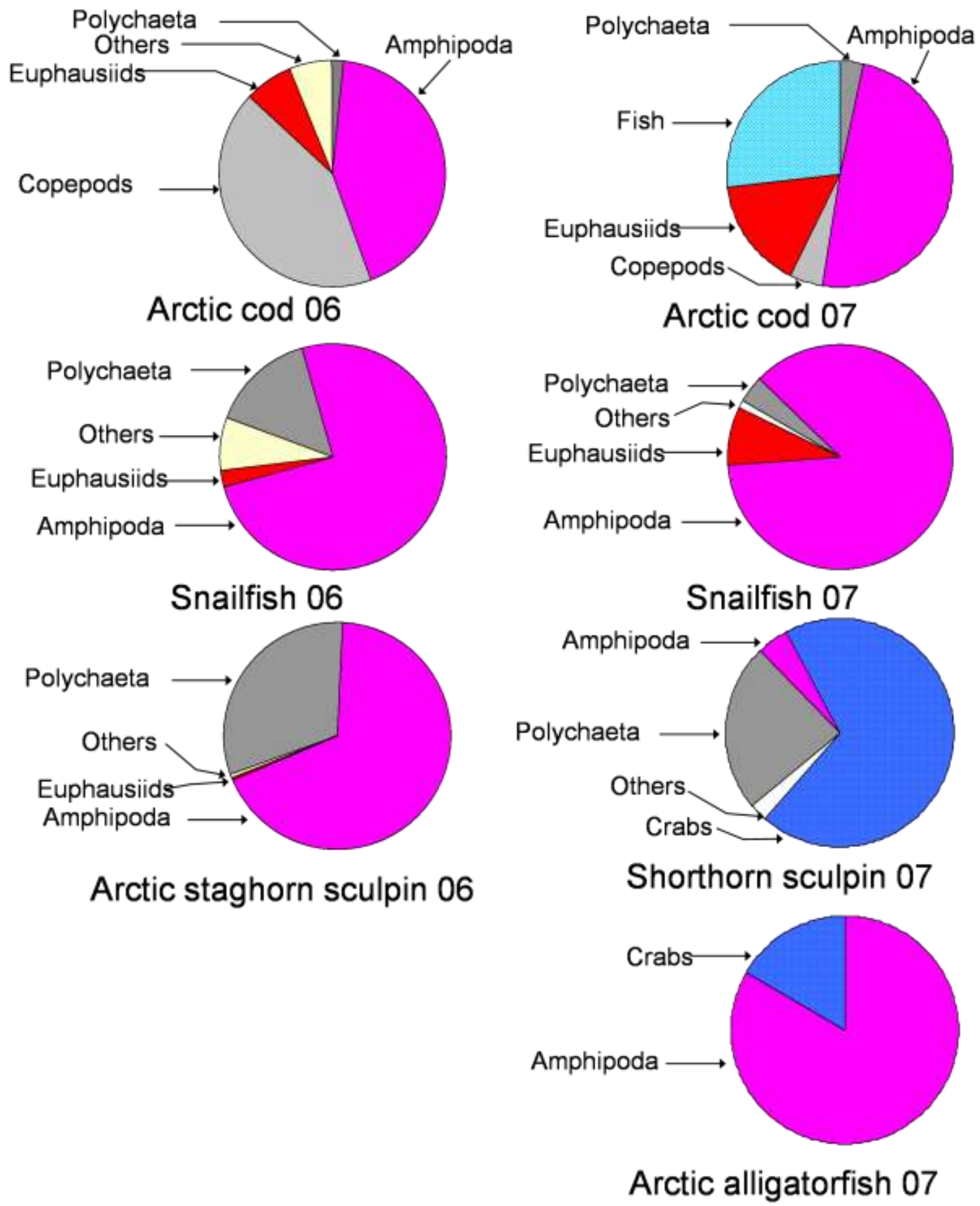


Fig. 3-2. Percentage by weight of major prey in the diet of dominant groundfish in the northern Bering Sea in 2006 and 2007. Key: 06 = 2006; 07 = 2007.

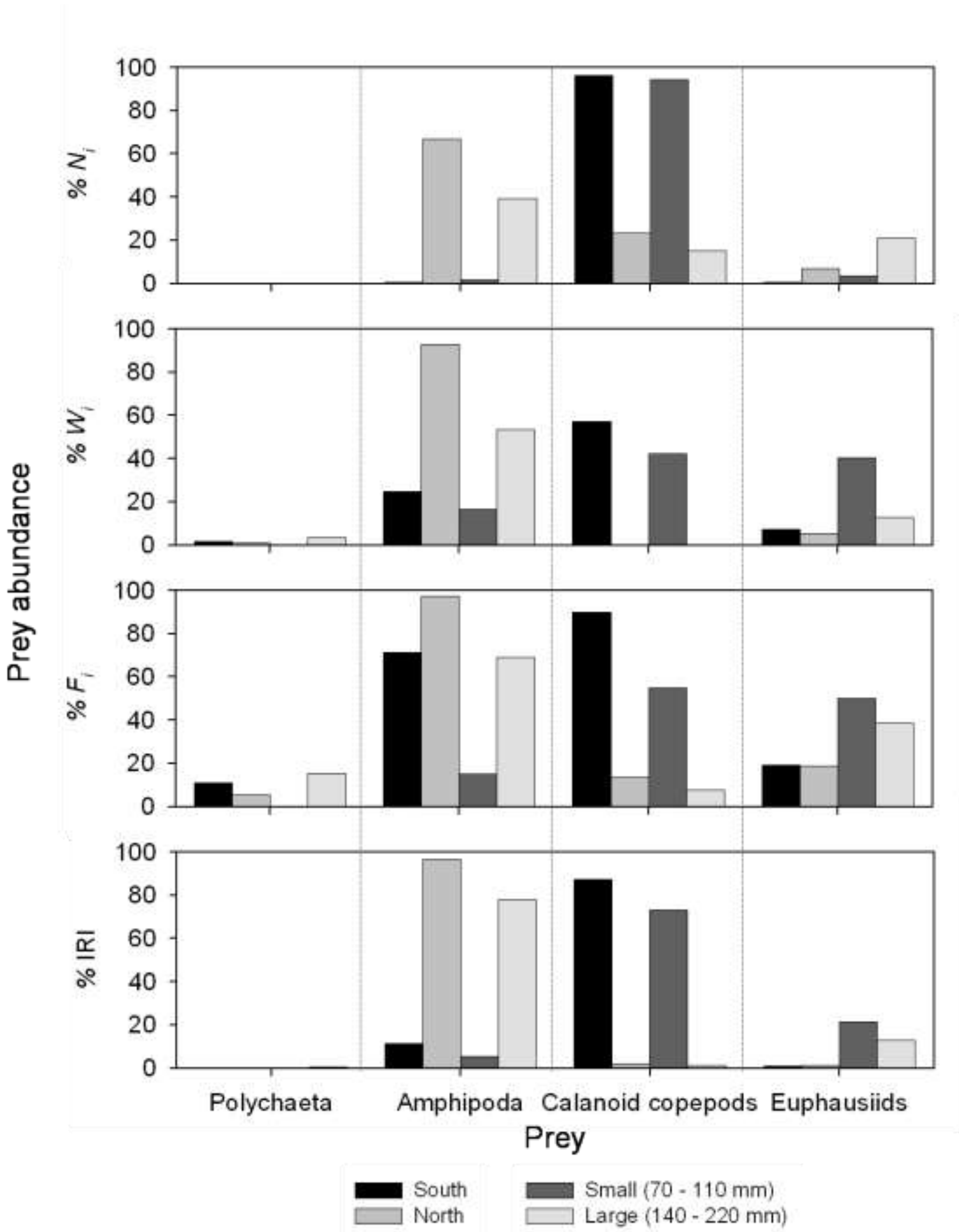


Fig. 3-3. Prey content of Arctic cod by location (south & north) in 2006 and size (small & large) in 2007 in the northern Bering Sea. N_i = numeric frequency; W_i = weight frequency; F_i = frequency of occurrence; IRI = proportional index of relative importance.

42.3% W_i, 55.0% F_i, 75.4% IRI), followed by euphausiid (40.2%) and oedicerotid amphipods (15.7%) by weight (Fig. 3-3). Large cod consumed fish (30.2% W_i) and amphipods (31.0% W_i) with members of the families Hyperiidae, Ampeliscidae, and Lysianassidae dominating (Fig. 3-3). Secondarily important prey were euphausiids by weight. Here, fish in stomachs were only 2% by number, but tended to bias results based on weight.

Snailfish: In 44 snailfish stomachs examined in 2006, benthic amphipods were the most important food (88.8 % N_i, 75.0 % W_i, 100.0 % F_i, 91.6 % IRI) (Table 3-1, Fig. 3-2), including the families Ampeliscidae (24.4%), followed by Lysianassidae (16.2%) and Melitidae (10.8%) families by weight. In the 144 stomachs sampled in 2007, benthic amphipods again predominated (87.9% N_i, 86.6% W_i, 94.4% F_i, 98.5% IRI) including the families Lysianassidae (40.5%), Melitidae (13.2%), and Ampeliscidae (11.1%) by weight (Table 3-2, Fig. 3-2).

Arctic staghorn sculpin: In 76 Arctic staghorn sculpin stomachs examined in 2006, benthic amphipods were the most important prey (22.0% N_i, 92.5% W_i, 100% F_i, 91.5% IRI), being dominated by members of the family Ampeliscidae (51.6% W_i) (Table 3-1, Fig. 3-2). Polychaetes (31.3% W_i) were the secondary prey with ampharetid polychaetes the most important followed by significant numbers of bivalve siphons (12.8% N_i).

Shorthorn sculpin: In 42 shorthorn sculpin stomachs examined in 2007, crabs (14.3% N_i, 69.1% W_i, 81.0% F_i, 41.0% IRI), benthic amphipods (46.5% N_i, 28.4% W_i, 83.3% F_i, 37.8% IRI), and polychaetes (21.0% N_i, 24.0% W_i, 71.4% F_i, 19.5% IRI) were the most common prey categories (Table 3-2, Fig. 3-2). Snow crab (*Chionoecetes opilio*) was the dominant prey species within the crab category; Melitidae was the most common within amphipod family; Ampharetidae was the most common within polychaete family (Fig. 3-4).

Table 3-2. Diet composition of Arctic cod, snailfish, and Arctic staghorn sculpin in the northern Bering Sea in 2007. N_i = numeric frequency; W_i = weight frequency; F_i = frequency of occurrence; IRI = proportional index of relative importance

	Arctic cod (n = 33)				**Snailfish (n = 144)**				**Shorthorn sculpin (n = 42)**				**Arctic alligatorfish (n = 6)**			
Prey	**%N_i**	**%W_i**	**%F_i**	**%IRI**	**%N_i**	**%W_i**	**%F_i**	**%IRI**	**%N_i**	**%W_i**	**%F_i**	**%IRI**	**%N_i**	**%W_i**	**%F_i**	**%IRI**
Polychaeta	0.0	3.2	6.1	0.3	0.3	3.9	23.6	0.6	32.1	24.0	71.4	22.6				
Ampharetidae									32.1	23.9	66.7	21.1				
Polynoidae	0.0	3.2	6.1	0.3	0.3	3.7	22.2	0.5								
Amphipoda	6.5	49.2	36.4	31.1	87.9	86.6	94.4	98.5	71.2	4.3	83.3	35.5	82.8	83.3	100	95.4
Ampeliscidae	1.8	13.6	15.2	3.6	11.6	11.1	31.3	4.2	3.6	0.2	2.4	0.1	65.5	44.1	100	63.0
Aoridae	0.1	0.1	3	0.0	1.2	0.6	3.5	0.0					10.3	3.6	16.7	1.3
Eusiridae									0.4	0.0	2.4	0.0				
Hyperiidae	2.1	8.2	9.1	1.4	0.2	0.0	0.7	0.0								
Isaeidae	0.3	0	6.1	0.0	12.9	1.2	19.4	1.6	0.2	0.0	2.4	0.0	3.4	0.1	16.7	0.3
Ischyroceridae					9.9	1.3	8.3	0.6								
Lysianassidae	0.9	5.6	3	0.3	35.4	40.5	42.4	19.2	1.9	0.5	19.0	0.3				
Melitidae					3.2	13.2	11.1	1.1	36.6	3.7	16.7	3.8				
Oedicerotidae	1.3	1.8	6.1	0.3	3.2	0.4	7.6	0.2								
Phoxocephalidae					0.9	0.1	1.4	0.0								
Stenothoidae					6.5	0.5	7.6	0.3								
Synoppidae					0.7	0.1	2.1	0.0								
Calanoid copepods	84.0	4.9	36.4	49.7	0.9	0.0	2.8	0.0								
Euphausiids	5.7	15.8	45.5	15.0	2.2	8.5	9.7	0.6	0.6	0.5	11.9	0.1				
Decapods (Shrimp)									0.7	1.1	4.8	0.0				
Cumacea	0.9	0.1	9.1	0.1	2.4	0.2	6.9	0.1	0	0.0	2.4	0.0				
Nuculana radiata					0.2	0.0	0.7	0.0								
Mollusc siphons									0.2	0.0	2.4	0.0	13.8	0.1	33.3	2.7
Cylichnidae					0.3	0.0	1.4	0.0								
Crabs									21.9	69.1	81.0	41.6	3.4	16.6	16.7	1.9
Chionoecetes opilio									9.5	61.5	69.0	27.7				
Hyas coarctatus									0.9	5.4	9.5	0.3				
Hermit crabs									11.2	1.8	4.8	0.4				
Isopods					4.3	0.0	5.6	0.1								
Fish	0.3	26.8	9.1	3.8	0.2	0.7	0.7	0.0								

Fig. 3-4. Photos of shorthorn sculpin prey in two stomachs. Above: Total length (TL) of sculpin = 352 mm, station: RUS2, Trawl: beam, included 50 ampharetid polychaete, one shrimp; Below: TL of sculpin = 352 mm, station: KIV3, trawl: beam, included two *Chionoecetes opilio*, one *Hyas coarctatus*, and four ampharetid polychaete.

Arctic alligatorfish: Most of the stomachs examined were either empty or filled with small amounts of sand in 2006 and 2007. In six stomachs examined in 2007, benthic amphipods (82.8% N_i, 83.3% W_i, 100% F_i, 95.4% IRI) were the most important prey, with Ampeliscidae (44.1% W_i) the most common amphipod family (Table 3-2, Fig. 3-2). Arctic alligatorfish also consumed significant numbers of bivalve siphons (13.8% N_i), and crabs (16.6%) by weight.

The diet composition in Arctic cod was significantly different ($\chi^2 = 144$, $p < 0.0001$) between the two size class groups in 2007, as well as in comparisons between 2006 and 2007 ($\chi^2 = 74$, $p < 0.0001$). Snailfish also had significant difference between the two years in prey composition (($\chi^2 = 94$, $p < 0.0001$)

Feeding strategies

Plots of the prey-specific index (P_i) against the frequency of occurrence (F_i) indicated that Arctic cod in 2006 and small cods in 2007 specialized on calanoid copepods, while large cods in 2007 specialized on benthic amphipods (Lysianassidae, Ampeliscidae) and copepods (Fig. 3-5). Snailfish preyed on various prey items, especially benthic amphipods, which were consumed by less than 50% of the total fish population in 2006 and 2007 (Fig. 3-5). Arctic staghorn sculpin and Arctic alligatorfish fed on the dominant prey – ampeliscid amphipods, with small proportions of other prey items consumed by small proportions of individuals (Fig. 3-5). Shorthorn sculpin showed specialization on ampharetid polychaetes and melitid amphipods by some individuals and opportunistic feeding on snow crab which might be biased by the low abundance in the stomachs (see Table 3-2, Fig. 3-5). All these fish species generally had narrow niches, except snailfish and large Arctic cod in 2007 (Fig. 3-5).

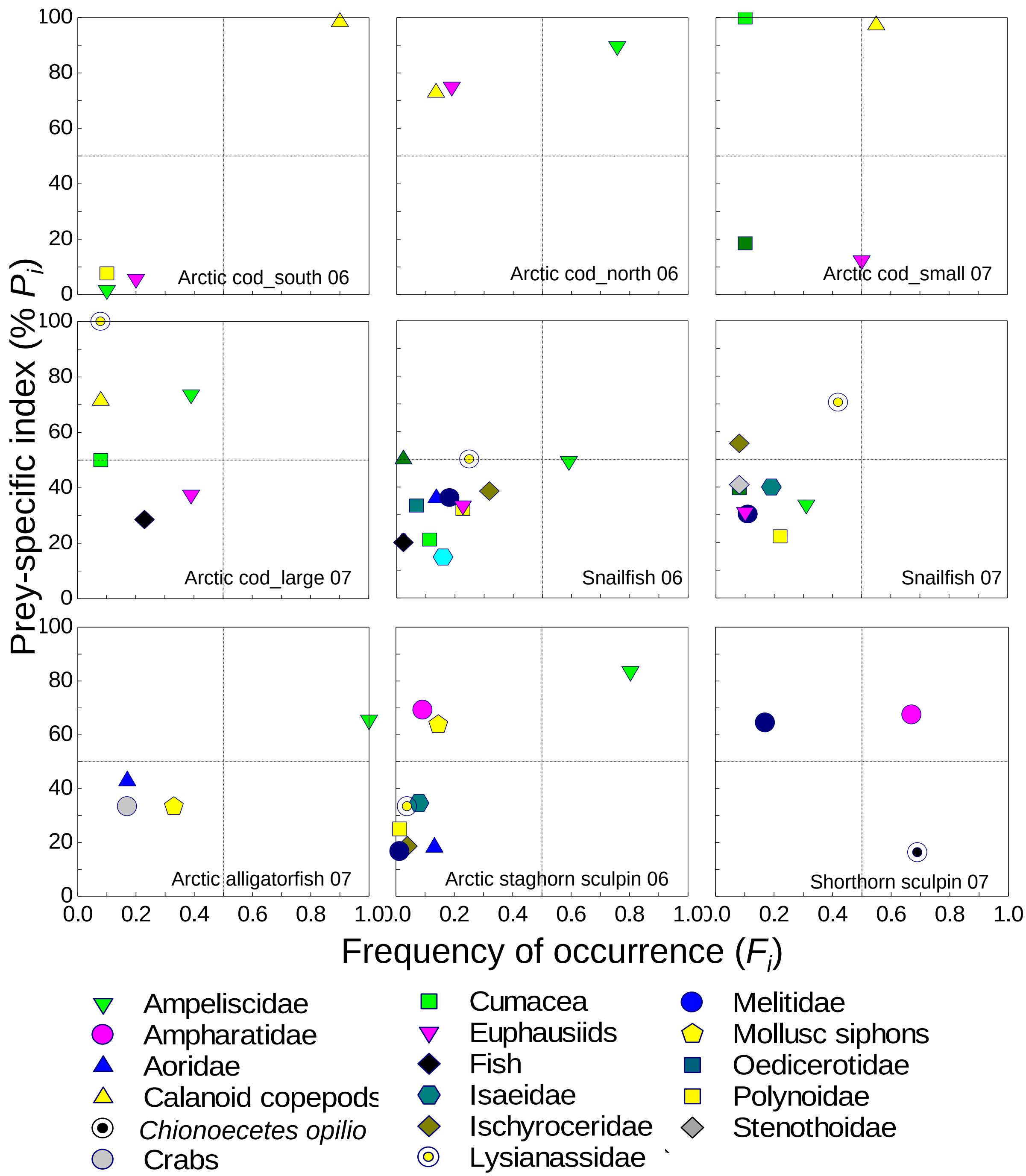


Fig. 3-5. Prey-specific index (P_i) vs. frequency of occurrence (F_i) for dominant groundfish in the northern Bering Sea. Key: 06 = 2006; 07 = 2007; south = south of SLI; north = north of SLI.

Diet overlap

Arctic cod in 2006 had complete (R_o = 1.0) overlap with small size Arctic cod in 2007 based on abundance, and had less overlap (R_o = 0.6) by biomass, although biologically significant (Table 3-3). Small prey items, such as copepods that contribute relatively little to overall food biomass bias the overlap index by abundance, in contrast with large prey items such as crabs or fish. Snailfish showed low overlap with other species for N_i in both years, but in 2006 snailfish had high dietary overlap with Arctic cod in 2006, the large size Arctic cod in 2007, snailfish in 2007, and Arctic alligatorfish for W_i (all ≥0.6, Table 3-3). Arctic staghorn sculpin had high dietary overlap with Arctic alligatorfish in both prey abundance and biomass (both ≥0.6, Table 3-3).

3.4 Discussion

Feeding behavior

Arctic cod: Benthic amphipods, calanoid copepods (pelagic), and euphausiids (pelagic) were the main prey of Arctic cod but in different proportions depending upon fish size, spatial differences and environmental conditions in this study. Lowry and Frost (1981) reported similarly that Arctic cod fed predominantly on benthos in the same area. In their studies (27 May – 10 June 1978) prey included ampeliscid amphipods, shrimps, and mysids. By comparison, Arctic cod consume predominantly pelagic amphipods and copepods in the Arctic Ocean. In shallow nearshore waters (<10 m), mysids have been found to be the main prey of Arctic cod

Table 3-3. Prey overlap (Shoener's index, R_0) based on numeric frequency N_i (below –) and on weight frequency W_i (above –); ≥0.6 are in bold. Key: AC = Arctic cod; SN = snailfish; ASS = Arctic staghorn sculpin; SS = shorthorn sculpin; AA = Arctic alligatorfish; 06 = 2006; 07 = 2007; S = small size; L = Large size

	AC06	SN06	ASS06	AC07S	AC07L	SN07	SS07	AA07
AC06	–	**0.6**	0.3	**0.6**	0.5	0.5	0.2	0.5
SN06	0.1	–	0.5	0.2	**0.6**	**0.7**	0.2	**0.7**
ASS06	0.3	0.5	–	0.1	0.3	0.3	0.3	**0.8**
AC07S	**1.0**	0.1	0.3	–	0.3	0.2	0	0.3
AC07L	0.3	0.4	0.5	0.3	–	0.5	0.2	0.5
SN07	0.1	0.5	0.5	0.1	0.4	–	0.1	0.5
SS07	0.2	0.3	0.5	0.1	0.3	0.2	–	0.3
AA07	0.1	0.5	**0.6**	0.0	0.3	0.2	0.2	–

both in summer and winter, with benthic amphipods and copepods also eaten by smaller fish sizes (mean ~100 mm, Craig et al. 1982). Collections near the surface and underneath the ice in winter (mean size ~92 mm, Craig et al. 1982) and collections from the bottom in summer (Lowry & Frost 1981, Coyle et al. 1997) indicated that calanoid copepods and pelagic amphipods were the predominant prey of Arctic cod in offshore waters of the Beaufort and Chukchi Seas. Several studies also found that small Arctic cod (<100 mm) ate mainly copepods, with pelagic amphipods increasing in importance in large Arctic cod (>100 mm, Bain & Sekerak 1978, Bohn & McElroy 1976, Hop et al. 1997). In our study, Arctic cod that occurred to the north of SLI to Bering Strait and of large size consumed primarily benthic amphipods, while Arctic cod to the south and of small size were mostly pelagic feeders. In our study, small Arctic cod were pelagic feeders, and large ones primarily benthic feeders in ice-free areas or low-ice conditions observed in our study area during the 2007 sampling season. Arctic cod are thought to be associated with ice for protection from predators and for feeding habitat (Crawford & Jorgenson 1993, Hop et al. 1997, Gradinger & Bluhm 2004). Arctic cod obtain significant energy through primary consumers, feeding on ice algal blooms during the ice-covered period (Lonne & Gulliksen 1989). In the northeastern Chukchi Sea, prey of Arctic cod are also thought to be related to the distributions of water masses (Coyle et al. 1997). Hop et al. (1997) also observed differences in feeding under schooling versus non-schooling conditions.

Other species: In our study, the dominant prey of Arctic staghorn sculpin were benthic amphipods (Ampeliscidae), followed by polychaetes (Ampharetidae) by biomass. By comparison, in the northeastern Chukchi Sea in summer (August – September), these fish consumed polychaetes (Ampharetidae, Flabelligeridae, *Nephtys* sp., Opheliidae and *Pectinaria* sp.) or euphausiids (*Thysanoessa* sp.) (Coyle et al. 1997). Although Bering flounder in our study did not consume any food at least several weeks before the sampling, fish caught in summer in the northeastern Chukchi Sea did prey on fish (mainly *Lumpenus* sp.) and crustaceans (*Byblis*, shrimps, crabs) (Coyle et al. 1997). From the same study, the stomach emptiness was higher in Bering flounder (25%) than in other demersal fishes (0 – 7%).

Potential competition for food resources

Arctic cod and snailfish shared the same habitat southwest of the SLI (Ch. 2; Cui et al. in revision). They had significant prey overlap in 2006 (R_0 = 0.6) and quite high overlap in 2007 (R_0 = 0.5) by biomass on their most common prey, benthic amphipods (Ampeliscidae and Melitidae), which also suggests competition between those two fishes for similar food resources (Fig. 3-6). However, snailfish occupy a broad niche with diverse benthic amphipods as prey, and the most important prey of Arctic cod are not benthic amphipods, but rather pelagic copepods.

Arctic staghorn sculpin and Arctic alligatorfish, which both occur north of SLI (Ch. 2; Cui et al. in revision), had significantly high prey overlap (R_0 > 0.6) by prey biomass and abundance. The two fish species share the same dominant prey, ampeliscid amphipods, and both occupy narrow niches; the highest concentration of ampeliscid amphipods (50 – 200 g m^{-2}) occurred in the same area where these two fish species dominate (Fig. 3-6).

Similarly, Arctic staghorn sculpin and shorthorn sculpin generally occur north of SLI (Ch. 2; Cui et al. in revision) with high overlap (R_0 = 0.5) of prey by abundance. Their most common prey item, ampharetid polychates (almost 25% of prey by weight), was also very high in biomass (~500 g m^{-2}) in some stations north of SLI (Fig. 3-6).

Our results indicate that the dominant groundfish in the northern Bering Sea are largely specialized feeders with narrow niches, with the exception of snailfish, which is an opportunistic feeder that occupies a broad niche. Although some of these dominant fish species share the same habitat and food resources, no strong evidence of competition is found.

In summary, our results indicate that benthic amphipods, particularly ampeliscid amphipods, are the most important prey for the dominant groundfish in the northern Bering Sea, except shorthorn sculpin. Ampharetid polychaetes were preferred prey by two sculpin species. Shorthorn sculpin and Arctic alligatorfish also consumed crabs. The only occasional planktonic feeder was Arctic cod which preyed on calanoid copepods and euphausiids in addition to benthic amphipods. Generally, snailfish consumed more diverse food items than all the other fish species. Although we only sampled two years, we consider the cold (2006) vs. warm (2007) comparison to provide insight on what may happen with northward migration of fish species. Additional

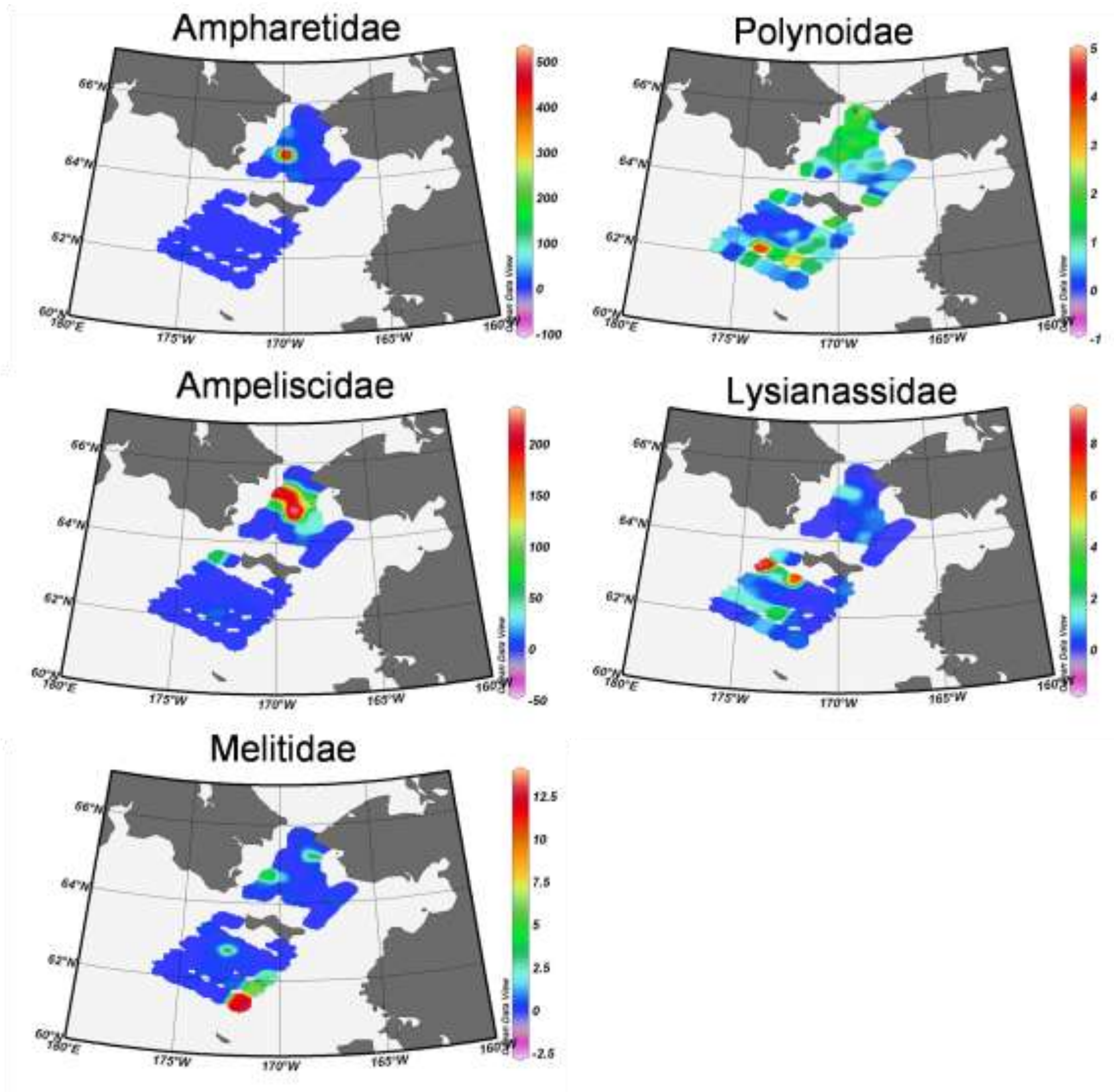


Fig. 3-6. Spatial pattern of selected prey items biomass in the northern Bering Sea. (unit: g wet weight m^{-2})

understanding of seasonal change and the trend of prey composition as the environmental system changes requires additional studies in the context of prey availability to fish populations.

Chapter 4

Trophic relationships of groundfish and prey evaluated through stable isotope analysis in the northern Bering Sea

This chapter is a paper to be submitted soon for publication by Xuehua Cui, Lee W. Cooper, Jacqueline M. Grebmeier, Zhenghua Li, Sang H. Lee, James W. Lovvorn. My use of "we" in this chapter refers to my co-authors and myself. Zhenghua Li performed the stable isotope ratio measurements and Sang H. Lee contributed samples from T/S *Oshoro Maru* 2007 cruise. My contributions to this paper include sampling groundfish, preparing samples for stable isotope analysis, analyzing data, and preparation of the manuscript.

4.1 Introduction

The northern Bering Sea is characterized by high nutrients and spring primary production due to the Pacific flow of water across this shelf system, particularly by Anadyr current water in the western sector. Low rates of zooplankton grazing in the spring occur due to cold water temperatures. Given the shallow depths, a net export of organic carbon to the benthos occurs that supports a rich benthic community (Grebmeier & Barry 2007). With the ongoing, but variable climate change influence on the reduction of sea ice extent and coincident increases in seawater temperatures, it is likely that the Arctic biological community will be affected (Overland &

Stabeno 2004, Grebmeier et al. 2006, Serreze et al. 2007, Mueter & Litzow 2008). The benthic-dominanted ecosystem on this shallow northern Bering shelf may well transition to a more pelagic-dominated system over time as sea ice and zooplankton grazing patterns change with continued climate warming (Grebmeier et al. 2006b, Grebmeier & Barry 2007). Ultimately trophic structure and coincident energy pathways of dominant organisms would also likely change.

Stomach content analyses are a traditional and direct approach in food web studies, but have some limitations. For example, these analyses only provide data on prey that were recently consumed, and not digested or assimilated before sampling. When the collected stomachs are empty or nearly empty, no direct diet assessment from stomach content analyses is possible. In addition, since epibenthic trawling is primarily restricted to the ice-free summer periods in seasonally ice-covered seas, such as the northern Bering Sea, there is a seasonal bias towards understanding fish consumption patterns in the summer, ice-free period only.

To strengthen food web studies, stable isotope analyses can be used to complement fish stomach content analyses. The stable isotope abundances of carbon (C) and nitrogen (N) in tissues are determined in part by the isotopic content in the diet (Fry & Sherr 1984, Michener & Schell 1994). Using this approach, stable isotope ratios have been used to estimate the relative trophic level status of fish and overall food web structure. Studies indicate an ~1‰ enrichment in $\delta^{13}C$ values per trophic level, while the enrichment in $\delta^{15}N$ values in a predator is generally 3 − 4‰ greater than its prey (McConnaughey & McRoy 1979, Hobson & Welch 1992, Rau et al. 1983, Post 2002). These and other studies indicate that $\delta^{15}N$ values are more sensitive to heavy isotope enrichment by trophic level than the stable carbon isotope composition. In marine polar ecosystems, $\delta^{13}C$ values of ice algae are more positive than pelagic particulate organic matter (POM) (Hobson & Welch 1992, Lovvorn et al. 2005, Søreide et al. 2006, Tamelander et al. 2006). By comparison terrestrial organic carbon is isotopically lighter (more depleted) than autochthonous organic carbon in aquatic systems (DeNiro & Epstein 1978). Among benthic faunal feeders, deposit feeders (such as bivalves) that consume both carbon transformed by microbial processing and bacteria themselves have higher enrichment of $\delta^{13}C$ values compared with benthic infauna consuming pelagic POM that had settled to the benthos (McConnaughey & McRoy 1979, Lovvorn et al. 2005). Because of these distinctions, $\delta^{13}C$ values can be used for differentiating organic carbon sources being consumed at the base of the food web.

In this study we used, $\delta^{13}C$ and $\delta^{15}N$ isotopic tracers to evaluate the food web structure and carbon sources in the northern Bering Sea. Our objectives were to: 1) evaluate the trophic levels of various groundfish species and their potential prey in the northern Bering Sea, and (2) to evaluate the seasonal and spatial differences in groundfish feeding behavior, both through stomach contents analyses and stable isotopic studies.

4.2 Materials and methods

Sampling. Most of the fish used in this study were collected in the northern Bering Sea (Fig. 4-1, Table 4-1) during two cruises on the USCGC *Healy* from 7 May to 5 June 2006 (HLY0601), and 16 May to 18 June 2007 (HLY0702) using otter and beam trawls. Additional groundfish

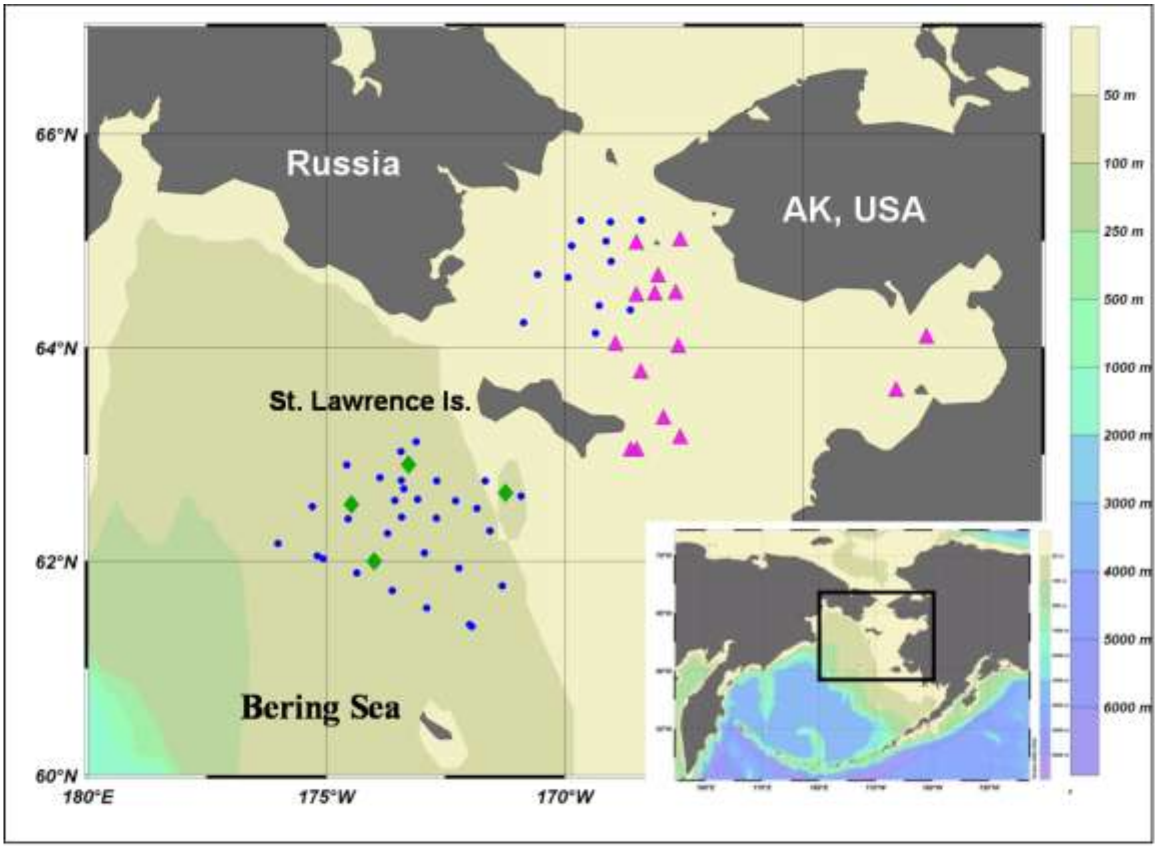


Fig. 4-1. Map of study area and sampling stations in the northern Bering Sea. Circles: HLY0601 & HLY0702; Triangles: NSEDC06; Diamonds : OM07. Key: HLY = USCGC *Healy*, NSEDC = Norton Sound Economic Development Corporation, OM = *Oshoro Maru*.

Table 4-1. Sampling date, and the range of depth, bottom water temperature, and bottom water salinity during four cruises

Cruise	Date	Depth (m)	Bottom water temperature (°C)	Bottom water salinity
HLY0601	7 May – 5 June 2006	35 – 96	-1.8 – -0.3	31.4 – 32.9
HLY0702	16 May – 18 June 2007	35 – 96	-1.7 – 0.6	32.3 – 33.1
NSEDC06	25 July – 19 August 2006	5 – 35	2.8 – 18.3	25.7 – 32.0
OM07	30 – 31 July 2007	40-70	-1.7 – -0.3	32.3 – 32.8

samples were collected during a survey supported by the Norton Sound Economic Development Corporation from 25 July to 19 August 2006 on R/V *Pandalus* (NSEDC06), and on a T/S *Oshoro-Maru* research cruise from 30 to 31 July 2007 (OM07, Fig. 4-1, Table 4-1). Zooplankton samples were collected by vertical plankton trawls with a 0.3 mm mesh net during HLY0702. Benthic invertebrate samples were collected using a 0.1 m^2 van Veen grab during HLY0702. Both zooplankton and benthic infaunal samples were frozen shipboard and subsequently shipped to the University of Tennessee for laboratory analyses. Fish samples were measured for total length (±1 mm) and a subsample of the dorsal muscle was removed for stable isotope analysis. Arctic alligatorfish (*Ulcina olrikii*) were too small to provide an adequate size subsample of muscle from the dorsal region, so the portion of the fish behind the anus was used for stable isotope analysis. Dorsal muscle tissues from groundfish and whole prey items of zooplankton and benthic invertebrates (using only the muscles from bivalves) were oven-dried at 60°C for 24

– 48 hrs. Dried samples were subsequently pulverized to a fine powder and stored in clean containers in the freezer until analyzed.

Stable isotope analysis. Approximately 1 mg (±0.001 mg) of dried ground sample was loaded in a 4 × 6 mm tin capsule for elemental content (% Carbon and % Nitrogen by weight) and stable C and N isotopic analyses. Samples were analyzed on a Thermo – Electron Delta plus XL isotope ratio mass spectrometer (IRMS), coupled to a Costech ECS4010 Elemental Analyzer (EA) at the Stable Isotope Laboratory in the Department of Earth and Planetary Sciences, University of Tennessee, Knoxville. Carbon (C%), Nitrogen (N%) contents, and C/N ratios of samples by mass were measured on the EA. Acetanilide (C_8H_9NO) was used as an EA standard to provide for C and N elemental concentration calibrations.

The $\delta^{13}C$ and $\delta^{15}N$ analyses were undertaken simultaneously. Internal standards for the stable C and N isotopes were prepared by the U.S. Geological Survey (USGS) and sold through the International Atomic Energy Agency (IAEA). The standards are each USGS40 ($\delta^{13}C$ = -26.39, $\delta^{15}N$ = -4.52) and USGS41 ($\delta^{13}C$ = 37.63, $\delta^{15}N$ = 47.57), which were analyzed at the same time as the samples to provide for accuracy and precision determinations (one standard for each six samples). The overall analytical deviation (SD) was ±0.08‰ for $\delta^{13}C$ and ±0.10‰ for $\delta^{15}N$.

Lipid normalization. Many studies have used either a chemical lipid extraction or a normalization relation to standardize $\delta^{13}C$ values for lipid concentrations in tissue (McConnaughey & McRoy 1979, Hobson & Welch 1992, Kling et al. 1992, Lesage et al. 2001, Sweeting et al. 2006, Post et al. 2007). Since increasing lipid content decreases ^{13}C values in tissues (McConnaughey & McRoy 1979, Hobson & Welch 1992, Post et al. 2007), adjustments are needed because prey in the Bering Sea have lipid contents varying between 1 and 55%

(McConnaughey & McRoy 1979). We decided to use a normalization procedure to account for lipid concentration effects on isotopic composition because the alternate lipid extraction methods can cause isotopic fractionation in $\delta^{15}N$ values (Sweeting et al. 2006, Post et al. 2007). Specifically, the equation to normalize C stable isotope ($\delta^{13}C'$) values in this study for organic tissues with C/N > 3.5 was $\delta^{13}C' = \delta^{13}C - 3.32 + 0.99 \times C/N$, and the relationship between C/N ratio and % lipid was % lipid = -20.54 + 7.24 × C/N (Post et al. 2007). Based upon recommendations of Post et al. (2007), we did not normalize when lipid content was less than 5% (C/N < 3.5), meaning this normalization procedure was limited to Pacific herring (*Clupea pallasii*), zooplankton, and prey items with high lipid contents, based on *a priori* evaluation of the literature.

Trophic structure. The trophic level (TL) of individual organisms was estimated using the following equation:

$$TL = 2 + (\delta^{15}N_{consumer} - 8.2) / 3.8$$

where $\delta^{15}N_{consumer}$ is the nitrogen isotope ratio of the consumer, 8.2‰ is the mean value of $\delta^{15}N$ of the primary consumer in this study, calanoid copepods, with an assumed TL 2.0, and 3.8‰ used as the average trophic enrichment value per trophic level (Hobson & Welch 1992 used 3.8‰). Vander Zanden and Rasmussen (2001) suggested that using a primary consumer TL = 2 as a baseline will induce a minor error in estimating TL compared to using a primary producer with a TL = 1. It should also be mentioned that different proportions of ice-algae and phytoplankton during the spring in the northern Bering Sea will also increase the variability in $\delta^{15}N$ value of the primary producer, if using TL = 1 as a baseline to estimate TL.

Statistical analyses. Statistical tests were performed with NCSS 2007 software (Number Cruncher Statistical System; Hintze 2009). Pair-wise multiple comparisons were performed to compare $\delta^{13}C$ and $\delta^{15}N$ values between different years, seasons, or spatial areas. We ran two-sample T-Test with equal variance; otherwise Aspin-Welch Unequal-Variance test was used with a Bonferroni alpha adjustment for the number of tests done (Hintze 2009). A randomization test was conducted with Monte Carlo sample size 10000 for each comparison test (see Ch. 2 Methods in Statistical analyses about randomization test).

4.3 Results

Groundfish had lower tissue C/N ratios than zooplankton or benthic invertebrates (Table 4-2). Fish in this study had average C/N ratios between 2.7 and 3.7 with calculated lipid contents (% lipid) of 0 – 6.2%, except one Pacific herring (*Clupea pallasii*) had a C/N ratio of 5.3 (calculated % lipid = 17.8%). Calanoid copepods had C/N ratios ranging from 5.6 – 11.9 (calculated % lipid = 19.8 – 65.6%) and benthic invertebrates had average C/N ratios ranging from 3.8 – 8.9 (calculated % lipid = 7.0 – 43.9%). Thus, the lipid normalized $\delta^{13}C'$ values differ from original $\delta^{13}C$ by up to 5.0‰ depending on the organism studied.

Seasonal variation in $\delta^{13}C$ within species. Muscle samples from summer 2006 (NSEDC06) were significantly different in $\delta^{13}C$ values from fish samples collected during other seasons, specifically for Alaska plaice (*Pleuronectes quadrituberculatus*), Arctic cod (*Boreogadus saida*) and snailfish (Liparidae) (Equal-Variance T-Test, $p < 0.05$) (Table 4-2, Fig. 4-2). In addition, Arctic cod had significantly higher $\delta^{13}C$ values in spring 2006 (HLY0601) than spring 2007

Table 4-2. Stable carbon (C) and nitrogen (N) isotopes, C/N mean (± SD) values of groundfish, zooplankton, and benthic invertebrates in the northern Bering Sea. $\delta^{13}C'$ is lipid-normalized $\delta^{13}C$ using the equation recommended by Post et al. (2007). TL is the estimated trophic level using a 3.8‰ enrichment value for $\delta^{15}N$ values for each TL above zooplankton. The sampling date of HLY0601 was from 7 May – 5 June 2006, HLY0702 was from 16 May – 18 June 2007, NSEDC06 was from 25 July – 19 August 2006, OM07 was from 30 – 31 July 2007. Key: n = sample size

Taxonomic group/ common name	Scientific name	Size (mm)	n	Cruise	$\delta^{13}C$	$\delta^{15}N$	C/N	$\delta^{13}C'$	TL
Fish									
Alaska plaice	*Pleuronectes quadrituberculatus*	225 – 310	7	HLY0601	-17.6 ± 0.5	16.9 ± 0.7	3.4 ± 0.3		4.3
		130 – 150	4	NSEDC06	-19.7 ± 0.5	17.1 ± 0.5	3.2 ± 0.0		4.3
		320 – 430	3	OM07	-17.2 ± 0.4	17.6 ± 0.9	3.3 ± 0.0		4.5
Arctic alligatorfish	*Ulcina olrikii*	45 – 78	23	HLY0601	-17.5 ± 0.6	15.7 ± 0.8	3.2 ± 0.2		4.0
		56 – 112	7	HLY0702	-18.8 ± 0.6	14.7 ± 1.4	3.4 ± 0.2		3.7
Arctic cod	*Boreogadus saida*	72 – 185	79	HLY0601	-19.4 ± 0.6	14.6 ± 0.5	3.3 ± 0.1		3.7
		69 – 108	17	HLY0702	-20.9 ± 0.6	13.8 ± 1.1	3.3 ± 0.1		3.5
		140 – 208	12	HLY0702	-20.3 ± 1.2	16.1 ± 1.4	3.4 ± 0.1		4.1
		118 – 172	7	NSEDC06	-20.0 ± 0.6	16.3 ± 0.7	3.3 ± 0.0		4.1
		183 – 197	3	OM07	-19.4 ± 0.6	15.4 ± 0.8	3.4 ± 0.0		3.9
Arctic staghorn sculpin	*Gymnocanthus tricuspis*	59 – 159	27	HLY0601	-18.3 ± 0.6	14.7 ± 0.9	3.3 ± 0.2		3.7
		70 – 99	3	HLY0702	-18.6 ± 0.4	13.9 ± 0.4	3.4 ± 0.0		3.5
		97 – 148	8	NSEDC06	-18.2 ± 0.5	17.0 ± 0.6	3.4 ± 0.1		4.3
Bering flounder	*Hippoglossoides robustus*	100 – 280	40	HLY0601	-18.6 ± 0.6	15.9 ± 1.2	3.3*		4.0
		105 – 227	25	HLY0702	-18.6 ± 0.5	16.3 ± 1.6	3.3 ± 0.0		4.1
		130 – 180	6	NSEDC06	-18.6 ± 0.5	16.6 ± 1.2	3.4 ± 0.1		4.2
		155 – 328	9	OM07	-18.7 ± 0.5	16.4 ± 0.9	3.3 ± 0.0		4.2

Table 4-2. Continued

Taxonomic group/ common name	Scientific name	Size (mm)	n	Cruise	$\delta^{13}C$	$\delta^{15}N$	C/N	$\delta^{13}C'$	TL
Capelin	*Mallotus villosus*	96 – 138	4	HLY0601	-20.1 ± 0.8	15.0 ± 0.9	3.7**		3.8
Pacific herring	*Clupea pallasii*	105 – 268	3	HLY0601	-21.9 ± 0.6	15.7 ± 1.0	5.3 ± 2.4	-20.0 ± 1.9	4.0
Shorthorn sculpin	*Myoxocephalus scorpius*	203 – 370	3	HLY0601	-17.8 ± 0.0	16.5 ± 1.1	3.2*		4.2
		257 – 375	16	HLY0702	-17.9 ± 0.3	16.1 ± 0.8	3.2 ± 0.1		4.1
Snailfish	Liparidae	78 – 133	15	HLY0601	-19.3 ± 0.3	17.2 ± 0.6	3.2 ± 0.1		4.4
		60 – 141	53	HLY0702	-19.8 ± 0.5	16.7 ± 1.2	3.3 ± 0.1		4.2
		90 – 180	7	NSEDC06	-18.7 ± 0.2	16.3 ± 0.6	3.2 ± 0.1		4.1
		300 – 340	5	NSEDC06	-18.2 ± 0.2	17.4 ± 0.9	3.3 ± 0.0		4.4
		147 – 230	9	OM07	-19.4 ± 0.4	16.9 ± 0.7	3.3 ± 0.0		4.3
Stout eelblenny	*Anisarchus medius*	82 – 145	8	HLY0601	-18.2 ± 0.4	17.8 ± 0.7	3.3*		4.6
Veteran poacher	*Podothecus veternus*	140 – 183	10	HLY0601	-18.0 ± 0.3	17.2 ± 0.7	3.6*		4.4
		137 – 177	6	NSEDC06	-18.2 ± 0.7	17.1 ± 0.7	3.6 ± 0.4		4.4
Walleye pollock	*Theragra chalcogramma*	73 – 96	12	HLY0601	-21.3 ± 0.4	15.4 ± 0.7	3.4 ± 0.0		3.9
		82 – 92	3	HLY0702	-21.0 ± 0.1	13.9 ± 0.2	3.3 ± 0.0		3.5
Yellowfin sole	*Limanda aspera*	201 – 230	2	HLY0601	-18.9 ± 1.4	16.8 ± 1.1	3.6 ± 0.4		4.3
		139	1	NSEDC06	-19.9	16.4	3.4		4.2
		264 – 316	3	OM07	-18.0 ± 0.4	16.8 ± 0.4	3.6 ± 0.0		4.3
Zooplankton									
Calanoid copepod	*Calanus* spp.		3	HLY0702	-23.5 ± 0.8	8.2 ± 2.3	8.1 ± 3.4	-18.9 ± 4.0	2.0

Table 4-2. Continued

Taxonomic group/ common name	Scientific name	Size (mm)	n	Cruise	$\delta^{13}C$	$\delta^{15}N$	C/N	$\delta^{13}C'$	TL
Benthic invertebrates									
Mollusca									
Bivalvia									
Byblis sp.			1	HLY0702	-23.6	11.0	8.3	-18.6	2.7
Macoma calcarea			4	HLY0702	-18.6 ± 0.3	9.8 ± 0.3	4.1 ± 0.2	-17.9 ± 0.4	2.4
Mussel			2	HLY0702	-18.5 ± 0.1	13.4 ± 0.2	3.9 ± 0.4	-19.1 ± 0.0	3.4
Nucula belloti		14 – 15	2	HLY0702	-18.5 ± 0.5	10.5 ± 1.0	3.8 ± 0.1	-18.1 ± 0.3	3.1
Nuculana radiata		18	1	HLY0702	-19.3	11.1	4.4	-18.3	2.6
Priplomatidae			1	HLY0702	-20.2	10.9	4.2	-19.3	2.8
Yoldia hyperborea		14	1	HLY0702	-19.2	9.7	3.9	-18.7	2.7
Crustacea									
Amphipoda									
Ampeliscidae			1	HLY0702	-23.9	12.3	8.4	-18.9	3.1
Hyperiidae			2	HLY0702	-23.1 ± 0.7	10.1 ± 1.2	7.7 ± 0.5	-18.8 ± 1.3	2.5
Lysianassidae			2	HLY0702	-19.9 ± 1.0	12.3 ± 1.0	8.9 ± 2.5	-14.4 ± 1.6	3.1
Melitidae			2	HLY0702	-19.3 ± 1.0	10.5 ± 0.8	5.6 ± 0.8	-17.1 ± 0.2	2.6
Sipunculida			1	HLY0702	-20.5	11.4	4.2	-19.7	2.8
Polychaeta									
Maldanidae			2	HLY0702	-20.5 ± 0.2	14.1 ± 0.6	4.5 ± 0.5	-19.4 ± 0.3	3.6
Nephtyidae			1	HLY0702	-18.1	16.1	3.8	-17.7	4.1
Pectinariidae			1	HLY0702	-20.8	15.4	5.1	-19.1	3.9
Polynoidae			3	HLY0702	-20.5 ± 1.3	15.7± 1.4	5.9 ± 2.3	-17.9	4.0

* C/N ratios were estimated from similar fish species;
** C/N ratio was from McConnaughey & McRoy (1979)

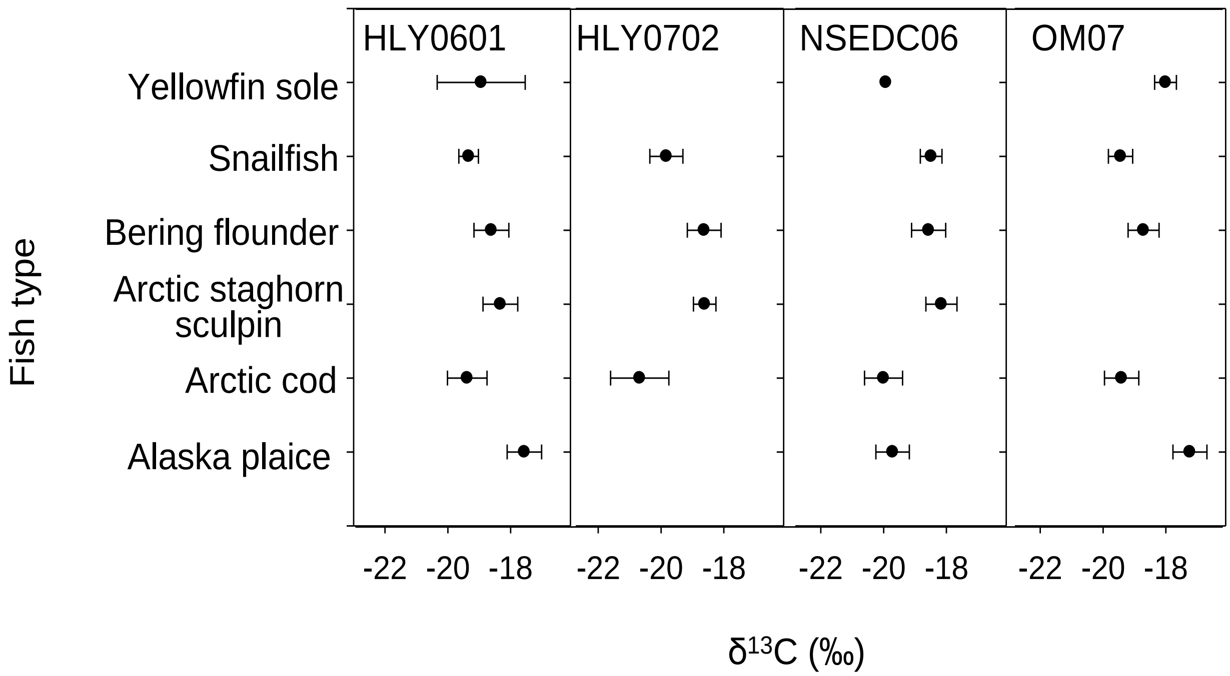


Fig. 4-2. Plot of $\delta^{13}C$ values (‰, mean ± SD) for six groundfish species, Alaska plaice, Arctic cod, Arctic staghorn sculpin, Bering flounder, snailfish, and yellowfin sole from four sampling seasons in the northern Bering Sea.

(HLY0702) (Aspin-Welch Unequal-variance Test) (Table 4-2, Fig. 4-2). Arctic staghorn sculpin (*Gymnocanthus tricuspis*) and Bering flounder (*Hippoglossoides robustus*) did not show any difference among sample seasons (Equal-Variance T-Test, $p > 0.05$) (Table 4-2, Fig. 4-2).

Spatial variation in δ^{13}C. In spring 2006 and 2007, there were enough samples of stable C and N isotope values for Arctic cod, Bering flounder, and snailfish to spatially plot the results showing longitudinal or latitudinal trends (Fig. 4-3). Arctic cod had significantly lower δ^{13}C values south of St. Lawrence Island (SLI) compared to values from samples north of SLI in spring 2006 (Equal-Variance T-Test, $p < 0.05$); this trend was not significant in spring 2007 (Equal-Variance T-Test, $p > 0.05$).

Since Bering flounder did not have significant differences in carbon isotope composition between spring 2006 and 2007 (Equal-Variance T-Test, $p > 0.05$), we combined both years and treated as a single data set in any further analyses. For example, Bering flounder found south of SLI had significantly (Equal-Variance T-Test, $p < 0.001$) lower δ^{13}C values than north of SLI. Snailfish south of SLI showed a decreasing trend of δ^{13}C values from west to east in 2007 (Fig. 4-3).

Seasonal variation in δ^{15}N. Arctic cod had no significant (Aspin-Welch Unequal-Variance Test, $p > 0.05$) difference between spring 2006 and 2007, while it had significantly (Equal-Variance T-Test, $p < 0.01$) lower δ^{15}N values in spring 2006 than summer 2006 and 2007. In 2006, δ^{15}N values of Arctic staghorn sculpin were significantly higher in summer than in spring (Equal-Variance T-Test, $p < 0.01$). The significant differences in δ^{15}N values in Arctic cod and Arctic staghorn sculpin resulted in up to a 0.6 differences in TL (Table 4-2).

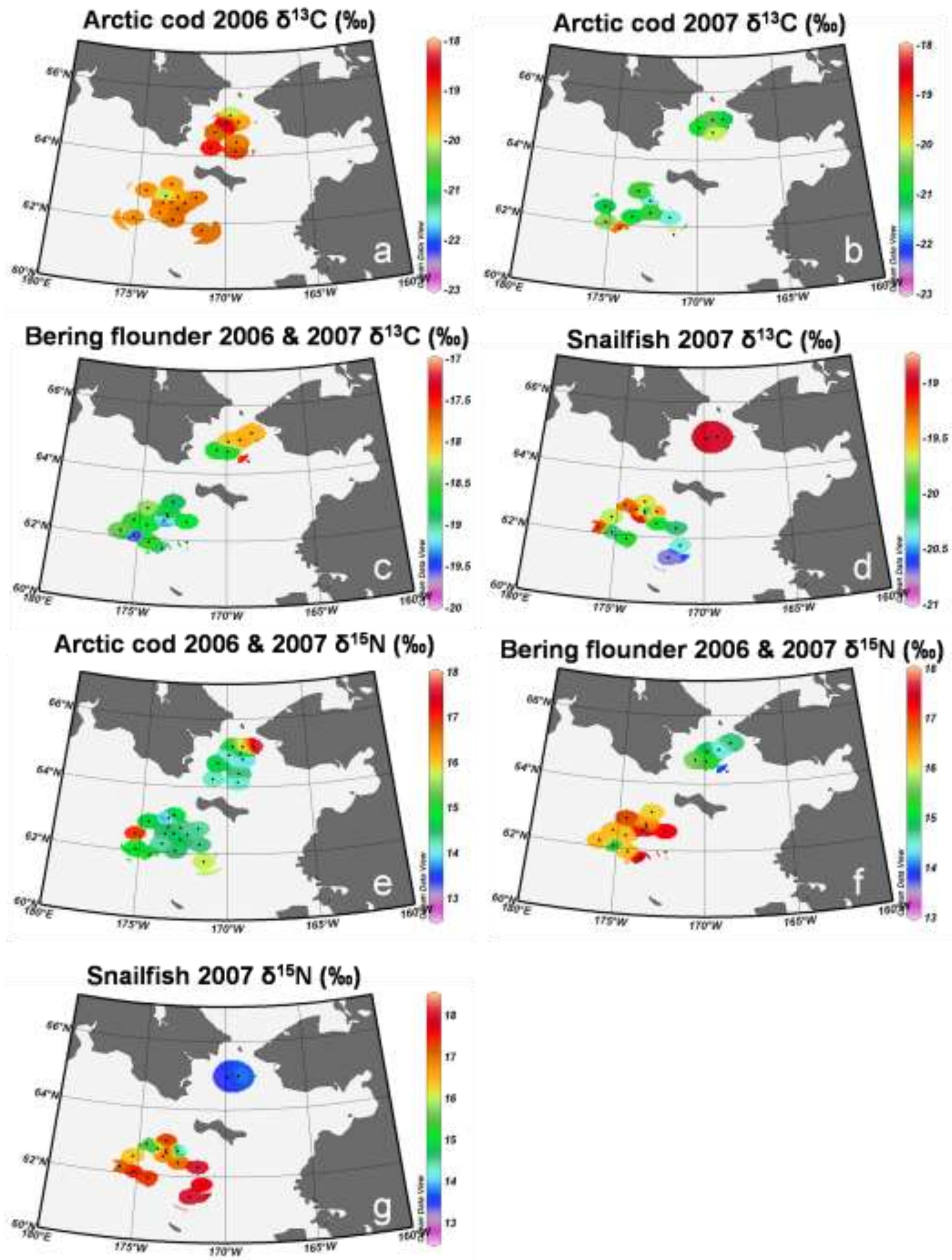


Fig. 4-3. Spatial distribution of three fish species: Arctic cod, Bering flounder, and snailfish from HLY0601 and HLY0702. Key: a-d: $\delta^{13}C$ (‰) and e-g: $\delta^{15}N$ (‰).

Spatial variation in δ^{15}N. Unlike the trend for δ^{13}C values outlined above, Arctic cod did not exhibit significantly (Aspin-Welch Unequal-Variance Test, $p > 0.05$) different δ^{15}N values spatially between south and north of SLI. However, this was not the case for Bering flounder, which had significantly (Equal-Variance T-Test, $p < 0.0001$) higher δ^{15}N values south versus north of SLI in spring 2006 and 2007. Snailfish had an increasing trend in δ^{15}N values from west to east in 2007 (Fig. 4-3).

The mean $\delta^{13}C'$ values of bivalves ranged from -19.3 for Priplomatidae to -17.9 for *Macoma calcarea*; that of amphipods ranged from -18.9 for Ampeliscidae to -14.4 for Lysianassidae; that of polychaetes ranged from -19.4 for Maldanidae to -17.7 for Nephtyidae; that of Sipunculida was -19.7 (Fig. 4-4, Table 4-2). The mean δ^{15}N values of bivalves ranged from 9.7 for *Yoldia hyperborea* to 13.4 for mussels; that of amphipods ranged from 10.1 for Hyperiidae to 12.3 for Ampeliscidae and Lysianassidae; that of polychaetes ranged from 14.1 for Maldanidae to 16.1 for Nephtyidae; that of Sipunculida was 11.4 (Fig. 4-4, Table 4-2).

4.4 Discussion

C/N ratios. Groundfish in this study had C/N ratios consistent with previous studies in the eastern Bering Sea (McConnaughey & McRoy 1979). Bottom fish in this study had low (<3.7) C/N ratios meaning lipid content was low enough not to have major influences on δ^{13}C values. However, a few pelagic fish in our study and a previous study (McConnaughey & McRoy 1979) had higher (up to 9.2) C/N ratios, resulting in up to 2.6‰ enrichment for δ^{13}C after lipid normalization.

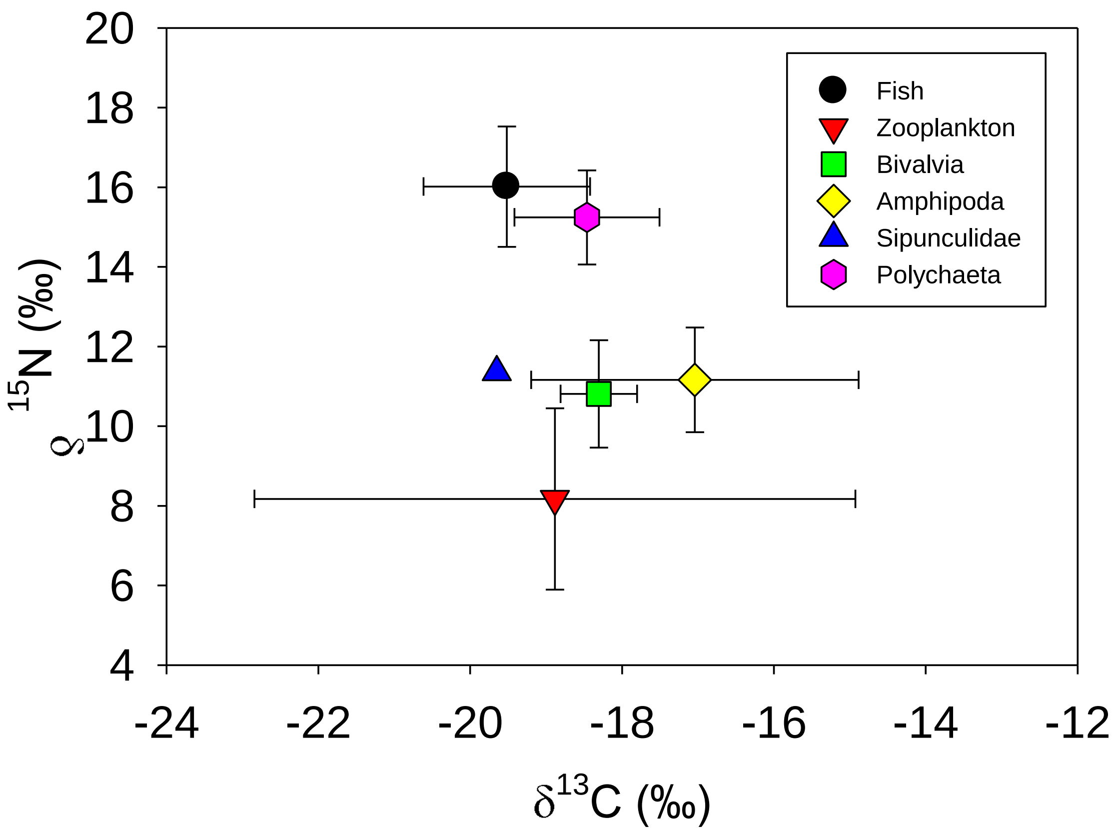


Fig. 4-4. Plot of $\delta^{13}C'$ (‰) and $\delta^{15}N$ (‰) values (mean ± SD) for fish and potential prey items in the northern Bering Sea from HLY0702. $\delta^{13}C'$ is lipid-normalized $\delta^{13}C$ using the equation recommended by Post et al. (2007).

C/N ratios of copepods and benthic invertebrates in our study had higher relative C content values compared to samples analyzed in the McConnaughey & McRoy (1979) study. This difference might be due to a higher food availability (phytoplankton biomass) for copepods and benthic invertebrates during our sampling season (May-June 2007) than the previous study (spring and summer of 1974 and 1975), or it could be due to spatial variance in processes between the region of our study area in the northern Bering Sea and the eastern region of the McConnaughey and McRoy (1979) study. Calanoid copepods also showed large variance in C/N ratios in our study. Samples of copepods from southwest of SLI (station NWC4A) had a mean C/N value of 6.1, while ratios of 11.9 were observed from an area southeast of SLI (station NEC2.5). Lee (1974) found that lipid storage in calanoid copepods occurred during the phytoplankton bloom in the Arctic Ocean. This finding might have significance for some of our data. For example, we arrived at station NWC4A 19 days before NEC2.5 (8 June 2007), and the varying evolution of the phytoplankton bloom may have impacted the lipid content of the zooplankton samples collected at that time. We observed, for example, that the isotopic composition of copepods at NEC2.5 ($\delta^{13}C' = -14.5$, $\delta^{15}N = 10.8$) was more positive than at NWC4A ($\delta^{13}C' = -21.1$, $\delta^{15}N = 6.9$). Copepods could have consumed more ice algal bloom at NEC 2.5 than at NWC4A, resulting in a more positive $\delta^{13}C$ value. Previous studies also found zooplankton depletion in $\delta^{13}C$ from the Beaufort Sea compared to the Chukchi and Bering Seas, and different fractionation in $\delta^{13}C$ might be related to feeding on variable phytoplankton species or amount, or internal metabolism changes (Rau et al. 1982, Schell et al. 1998). For $\delta^{15}N$, it has been found that the variability in stable nitrogen isotopes in herbivores (e.g copepods) is much greater than that found at higher trophic levels (TL > 2) (Vander Zanden & Rasmussen 2001).

Benthic melitid amphipods that are most abundant to the southeast of SLI (see Ch. 3) have lower lipid concentrations than other benthic amphipods which dominate in the southwest of SLI (Lysianassidae), or north of SLI (Ampeliscidae). Benthic biomass and primary production are higher both southwest and north of SLI than southeast of SLI (Grebmeier & Barry 2007). The southeast region of SLI has a lower benthic biomass due to reduced levels of primary production characteristic of the Alaska coast water (Grebmeier et al. 2006b).

Stable carbon isotopes. Stable isotope results in this study are consistent with stomach content analyses undertaken on the same fish samples (Ch. 3). In spring 2006, Arctic cod consumed ~50% copepods, and the other ~50% of the stomach contents were benthic amphipods (see Ch. 3). By comparison, in spring 2007 Arctic cod fed ~50% on copepods and 27% on fish in spring 2007 (see Ch. 3). These fish occuring in the stomachs of Arctic cod were either juvenile Arctic cod or walleye Pollock, which have isotopically low $\delta^{13}C$ values, causing Arctic cod to have low $\delta^{13}C$ values in spring 2007 in this study. In addition, prey composition in the stomach contents of Arctic cod in our study also showed a difference between south and north of SLI in spring 2006, which is consistent with the variable $\delta^{13}C$ values observed in the prey. From the standpoint of carbon isotopes, our results indicate that Arctic cod fed proportionally more on isotopically heavier benthic amphipods north of SLI than Arctic cod south of the island, where they depended on isotopically ligher copepods (see Ch. 3).

The primary prey of snailfish collected during our study were benthic amphipods (75 – 87% by biomass in stomach samples) and there were large differences in prey composition between 2006 and 2007 spring seasons (see Ch. 3). We suspect that benthic invertebrates such as amphipods collected during the warmer spring 2007 period, had fresher phytodetrital materials settling during the main spring phytoplankton bloom than in the colder spring period of 2006 when the bloom was later than we sampled. This difference in seasonal productivity likely caused the significantly low $\delta^{13}C$ values for snailfish in spring 2007 vs. spring 2006. Snailfish also showed a longitudinal trend in $\delta^{13}C$ values in the sector south of SLI where snailfish prey more on isotopically heavier lysiannassid amphipods to the west and more on isotopically lighter ampeliscid amphipods in the east in spring 2007. The percent of prey biomass in stomachs of snailfish in the west and east were 43.9% and 3.4% on lysiannassid amphipods, while 7.5% and 47.9% on ampeliscid amphipods. In addition, a west-to-east decrease in $\delta^{13}C$ values for sediment organic matter and copepods in the Bering Sea is also observed due to changes in water mass type, specifically Anadyr water in the west and Alaska coastal water in the east (Schell et al. 1998, Naidu et al. 2000, Cooper et al. 2002). This longitudinal variation in $\delta^{13}C$ values is likely due to the influence of Alaskan rivers that contribute terrestrial carbon with more negative $\delta^{13}C$ values to the east and less heavy-isotope depleted organic carbon from phytoplankton to the west generated within the more nutrient-rich Anadyr water (Schell et al. 1998, Naidu et al. 2000, Cooper et al. 2002).

The mean $\delta^{13}C'$ values for groundfish were correlated to the estimated TL using $\delta^{15}N$ values and to the increase of $\delta^{13}C$ per TL which was 1.8‰ (Fig. 4-5). This finding is consistent with the 1.5‰ isotopic enrichment observed per trophic level by McConnaughey and McRoy (1979) for their Bering Sea food web study. Zooplankton and benthic invertebrate prey, however, did not show significant increase in $\delta^{13}C'$ value from the food base to consumers (Fig. 4-5). This observation of no significant $\delta^{13}C'$ enrichment of benthic invertebrates relative to that of

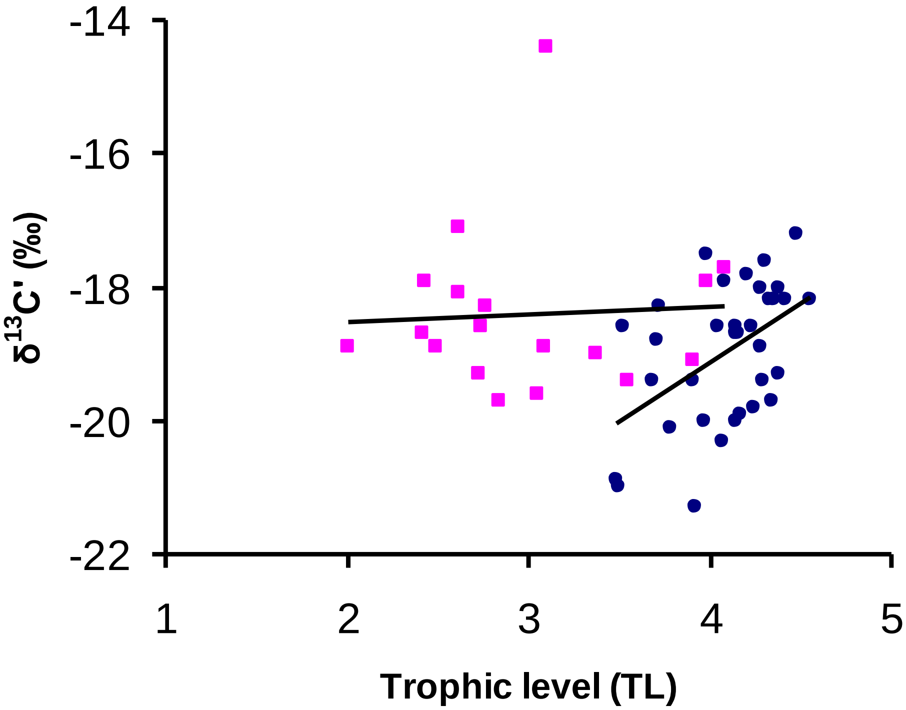


Fig. 4-5. Plot of trophic level (TL) and $\delta^{13}C'$ (‰) for groundfish and prey. Blue circles: groundfish; pink rectangles: zooplankton and benthic invertebrates. The trend for groundfish is $\delta^{13}C' = 1.76 \times TL - 26.17$ ($r^2 = 0.24$, $t = 3.18$, $p < 0.05$), while zooplankton and benthic invertebrates ($t = 0.19$, $p > 0.05$). $\delta^{13}C'$ is lipid-normalized $\delta^{13}C$ using the equation recommended by Post et al. (2007).

zooplankton reflects strong pelagic-benthic coupling in this region as in the Chukchi Sea (Dunton et al. 2006).

The lack of stomach contents in Bering flounder makes it hard to evaluate our stable isotope data but the difference in $\delta^{13}C$ values between north and south of SLI are probably caused by differences in prey that they consumed prior to sampling.

The mean $\delta^{13}C$ value for benthic amphipods showed the greatest enrichment in ^{13}C in all benthic invertebrates sampled in this study (Fig. 4-4). This observation may be due to the diverse feeding mode of the different benthic amphipods found in the study. Suspension feeders might consume a greater quantity of fresh particles provided to the seafloor with a lighter isotopic signature before bacterial degradation occurs in the surface sediments, while deposit feeders and carnivores that consume the isotopically enriched materials reworked by bacteria and meiofauna ultimately would consume food with a heavier ^{13}C signature. For example, ampeliscid amphipods are both suspension and surface deposit feeders on fresher phytodetritus compared to melitid amphipods that are detritivores (Nicolas et al. 2007 and references therein). Note that lysianassid amphipods are scavengers, thus they prey on a variety of organic carbon forms.

Stable nitrogen isotopes. The mean $\delta^{15}N$ value of 8.2‰ for calanoid copepods is lower than the values reported from other studies in the same area (9.6‰ by Schell et al. 1998, 11.1‰ by Lovvorn et al. 2005).

The trophic level of Arctic cod is 3.5 for juveniles (<110 mm), and slightly higher for adults (TL = 3.7 – 4.1, >110 mm). Juvenile Arctic cod feed more on copepods and adult Arctic cods feed more on ^{15}N enriched benthic amphipods. In spring 2006 (HLY0601), 95% of the fish samples were large specimens with slightly lower TL than samples from other seasons (summer

2006, spring and summer 2007). This finding is consistent with stomach content analyses (see Ch. 3) where Arctic cod had preyed more on copepods (42.5% in biomass, TL = 2) in spring 2006, while they preyed more on benthic amphipods and fish (49.2% and 26.8% each, TL > 2) in spring 2007. In addition, Arctic cod consume higher proportions of benthic amphipods in the Bering Sea, while copepods are their main prey in both the Chukchi or Beaufort seas (see Ch. 3). Therefore, Arctic cod from this study have higher TL values than fish from the Arctic Ocean proper. In the Barents Sea for example, the TL of Arctic cod range from 3.3 – 3.8 (Søreide et al. 2006, Tamelander et al. 2006).

The stepwise $\delta^{15}N$ enrichment from zooplankton (copepods, TL = 2) to bivalves and benthic amphipods was 1.6 – 4.5‰ (TL = 2.4 – 3.2), and reached even higher levels in polychaetes, 5.9 – 7.9‰ (TL = 3.6 – 4.1). One possible explanation is that the bivalves and amphipods analyzed are selective surface deposit feeders, which feed on more freshly deposited particles that are isotopically lighter because there has been less time for bacterial transformations within the sediments. By comparison, polychaetes in the study area are more likely to be deposit feeders on organic matter that has been re-worked. Bivalves can be both surface and subsurface deposit feeders whereas benthic amphipods are both suspension and surface deposit feeders.

$\delta^{15}N$ enrichment of benthic invertebrates from the base food source was less in this study than other areas. Generally, regions of high pelagic-benthic coupling result in short food webs and higher benthic production, while areas of less export of carbon to the benthos results in longer food chains and lower benthic production (Grebmeier et al. 1989, Grebmeier & Dunton 2000, Dunton et al. 2006).

The results of our study indicated that the combination of stable isotopic data with prey content analyses provide for a stronger data set to interpret the changes in $\delta^{13}C$ or $\delta^{15}N$ values within the food web. However, our study helps convey the complexity of stable isotopic variability because the stable isotope analyses alone cannot explain whether differences are caused by food source availability or stable isotope variation in prey due to environmental factors (Fry et al. 2008 and references therein). Thus, our work emphasizes the importance of combined use of fish stomach contents and predator-prey isotopic analyses to provide more insights into food web relationships of fish-prey populations.

Chapter 5

Conclusion

5.1 Groundfish distribution and environmental impacts

Benthic fish communities are distributed in two main groups in the northern Bering Sea. One group located south of SLI includes Arctic cod, Bering flounder and snailfish. The other group located north of SLI includes Arctic alligatorfish and Arctic staghorn sculpin, or shorthorn sculpin. The distributions of co-occuring groundfish communities were similar between the two different years, while fish were generally more abundant in the warm year (2007) than cold year (2006), except for Arctic cod, which is a cold water fish. Our results suggest that more fish will occur further north in the northern Bering Sea as sea water warms and sea ice retreats, with a coincident reduction in the SLIP cold pool.

Among all 14 environmental factors, bottom water temperature, depth, sediment grain size, TOC, and TON were significantly different between the two station groups over the two years' studied. Bottom water chlorophyll *a* and integrated water column chlorophyll *a*, however, were significantly different in pre-bloom vs. bloom conditions, thus having variable influence on the fish communities The highest environmental factors correlated to fish communities were sediment grain size and water column nutrients during cold, pre-bloom conditions, while sediment grain size and seawater temperature were the environmental factors influencing fish community structure in warm and bloom conditions. Fish population are influenced more by hydrographic conditions during the colder, prebloom conditions, and more by temperature later in the season sea water is warmer and the spring bloom has occurred. In addition, fish abundance and distribution are always influenced by current speed, as indicated by sediment grain size.

5.2 Feeding habitat of groundfish

Benthic amphipods are the predominant prey for the four dominant groundfish in the study area. Ampeliscid amphipods are the dominant benthic prey and are most abundant north of SLI. Arctic staghorn sculpin and Arctic alligatorfish prey mostly on ampeliscid amphipods and also are dominant benthic fish north of SLI. Snailfish also consume ampeliscid amphipods, although they occur south of SLI; however, they consume a variety of amphipods including species of the families Lysianassidae and Melitidae as well. Only snailfish have a broad niche; the other fish species have narrow niches. In addition to amphipods, the two sculpin species (Arctic staghorn sculpin and shorthorn sculpin) consume a variety of polychataes, especially members of the family Ampharetidae. More than 80% of shorthorn sculpin also consume crabs (mainly snow crabs). Only some fish have bivalves in their stomachs. However, mollusc siphons are found in up to one third of Arctic alligatorfish and Arctic staghorn sculpin, indicating a potential dietary preference when these bivalves are present.

Arctic cod is the only vertically migrating species, feeding on copepods in the water column. Benthic amphipods were consumed more in waters north of SLI by large Arctic cod, or in the year with colder and icy conditions. Copepods or other water column prey (such as euphausiids) were eaten more south of SLI, or in open water condition by small size Arctic cod.

Some benthic fish species share the same habitat and food resources. However, diversity of food resources is evident even where habitat is shared. Our results indicate that there is no strong evidence for competition among fish communities in the northern Bering Sea.

5.3 Food web structure in groundfish

Groundfish in this study area have low lipid contents, thus only minor influences on $\delta^{13}C$ values are likely for bulk tissues. The influence of higher lipid contents on stable isotope ratios in both zooplankton and benthic invertebrates were accounted for using a mathematical normalization based on the C/N ratio of the tissue sample. Arctic cod showed spatial differences in $\delta^{13}C$ values south and north of SLI, likely a result of different proportions of prey, such as isotopically lighter copepods and heavier benthic amphipods in the two regions, respectively. Snailfish showed a west-east trend in $\delta^{13}C$ values south of SLI where snailfish prey more on isotopically heavier lysiannassid amphipods to the west and more on isotopically lighter ampeliscid amphipods in the east. This trend also reflects variation in $\delta^{13}C$ values for sediment organic matter in this region due to changes in water mass type. The results of our stable isotope analyses are generally consistent with the results from the stomach content analyses. Trophic levels (TL) of fish and prey were estimated by $\delta^{15}N$ values, using the primary consumer as a baseline indicator. Bivalves and amphipods had the lowest TL = 2.4 – 3.4, followed by polychaetes (TL = 3.6 – 4.1), and fish (TL = 3.5 – 4.6). The mean $\delta^{13}C$ values for groundfish were correlated to the estimated TL using $\delta^{15}N$ values and to the increase of $\delta^{13}C$ by 1.8‰ per TL. Both low $\delta^{13}C$ and $\delta^{15}N$ enrichments indicate that benthic invertebrates are tightly coupled to pelagic production in this region, where organic carbon export is high, resulting in high benthic biomass.

Our findings are consistent with the suggestions that more groundfish will likely move northward with a continued sea water warming trend, since the fish distributions we studied are best correlated to water temperatures in warm conditions. Currently, the groundfish species studied don't apparently compete much with each other. However, our study is based on only two spring seasons, and thus the data are limited in their capability to address seasonal changes and long-term trends over multiple years. Future research should include multi-seasonal surveys in this region, including time series ecological studies in order to increase our understanding of ongoing changes of fish distribution and seasonal variance.

List of References

List of References

Ainley DG, DeMaster DP (1990) The upper trophic levels in polar marine ecosystems. In: Smith WO Jr (ed) Polar Oceanography. Part B: Chemistry, Biology and Geology. 599-630

Alexander V, Niebauer HJ (1981). Oceanography of the eastern Bering Sea ice-edge zone in spring. Limnol Oceanogr 26:1111-1125

Amundsen PA, Gabler HM, Staldvik FJ (1996) A new approach to graphical analysis of feeding strategy from stomach contents data—modification of the Costello (1990) method. J Fish Biol 48:607-614

Anderson PJ, Piatt JF (1999) Community reorganization in the Gulf of Alaska following ocean climate regime shift. Mar Ecol Prog Ser 189:117-123

Andriyashev AP (1964) Fishes of the northern seas of the USSR. Israel program for scientific translations, Jerusalem

Aydin K, Mueter F (2007) The Bering Sea—A dynamic food web perspective. Deep-Sea Res II 54:2501-2525

Bain H, Sekerak AD (1978) Aspects of the biology of arctic cod, *Boreogadus saida*, in the central Canadian Arctic. Report by LGL Ltd., Toronto, for Polar Gas Project, Toronto. 104p

Bluhm BA, Gradinger R (2008) Regional variability in food availability for Arctic marine mammals. Ecol Appl 18:S77-S96

Bohn A, McElroy RO (1976) Trace metals (As, Cd, Cu, Fe and Zn) in Arctic cod, *Boreogadus saida*, and selected zooplankton from Strathcona Sound, northern Batfin Island. J Fish Res Board Can 33:2836-2840

Bradstreet MSW, Finley KJ, Sekerak AD, Griffiths WD, Evans CR, Fabijan MF, Stallard HE (1986) Aspects of the feeding ecology of Arctic cod (*Boreogaidus saida*) and its importance in Arctic marine food chains. Can Tech Rep Fish Aquat Sci 1491:1-193

Brodeur RD, Wilson MT, Walters GE, Melnikov IV (1999) Forage fishes in the Bering Sea: Distribution, species associations, and biomass trends. In: Loughlin TR, Ohtani K (eds) Dynamics of the Bering Sea. University of Alaska Sea Grant, Fairbanks, Alaska, p 509-536

Clarke KR, Warwick RM (2001) Change in Marine Communities: An Approach to Statistical Analysis and Interpretation, second ed. PRIMER-E Plymouth, UK. http://www.primer-e.com/

Clement JL, Cooper LW, Grebmeier JM (2004) Late winter water column and sea ice conditions in the northern Bering Sea. J Geophys Res 109 (C3), C03022

Clement JL, Maslowski W, Cooper LW, Grebmeier JM, Walczowski W (2005) Ocean circulation and exchanges through the northern Bering Sea—1979–2001 model results. Deep-Sea Res II 52:3509-3540

Cooper LW, Grebmeier GM, Larsen IL, Egorov VG, Theodorakis C, Kelly HK, Lovvorn JR (2002) Seasonal variation in sedimentation of organic materials in the St. Lawrence Island polynya region, Bering Sea. Mar Ecol Prog Ser 226:13-26

Conover RJ, Siferd TD (1993) Dark-season survival strategies of coastal-zone zooplankton in the Canadian arctic. Arctic 46:303-311

Cortés E (1997) A critical review of methods of studying fish feeding based on analysis of stomach contents: application to elasmobranch fishes. Can J Fish Aquat Sci 54:726-738

Coyle KO, Gillispie JA, Smith RL, Barber WE (1997) Food habits of four demersal Chukchi Sea fishes. Am Fish Soc Symp 19:310-318

Coyle KO, Pinchuk AI (2002) Climate-related differences in zooplankton density and growth on the inner shelf of the southeastern Bering Sea. Prog Oceanogr 55:177-194

Craig PC, Griffiths WB, Haldorson L, McElderry H (1982) Ecology studies of Arctic cod (*Boreogadus saida*) in Beaufort Sea Coastal Waters, Alaska. Can J Fish Aquat Sci 39:395-406

Crawford RE, Jorgenson JK (1993) Schooling behaviour of arctic cod, *Boreogadus saida*, in relation to drifting pack ice. Environ Biol Fish 36:345-357

Cui X, Grebmeier JM, Cooper LW, Lovvorn JR, North CA, Kolts JM (in revision) Spatial distributions of groundfish in the northern Bering Sea in relation to environmental variation.

Danielson S, Aagaard K, Weingartner T, Martin S, Winsor P, Gawarkiewicz G, Quadfasel D (2006) The St. Lawrence polynya and the Bering shelf circulation: New observations and a model comparison. J Geophys Res 111:C09023

Davis AJ, Jenkinson LS, Lawton JH, Shorrocks B, Wood S (1998) Making mistakes when predicting shifts in species range in response to global warming. Nature 391:783-786

DeNiro MJ, Epstein S (1981) Influence of diet on the distribution of nitrogen isotopes in animals. Geochim Cosmochim Acta 45:341-351

Dolbeth M, Martinho F, Leitão R, Cabral H, Pardal MA (2008) Feeding patterns of the dominant benthic and demersal fish community in a temperate estuary. J Fish Biol 72:2500-2517

Dolch T, Hass HC (2008) Long-term changes of intertidal and subtidal sediment compositions in a tidal basin in the northern Wadden Sea (SE North Sea). Helgol Mar Res 62:3-11

Dunton KH, Weingartner T, Carmack EC (2006) The nearshore western Beaufort Sea ecosystem: Circulation and importance of terrestrial carbon in arctic coastal food webs. Prog Oceanogr 71:362-378

Eschmeyer WN, Herald ES, Hammann H (1983) A field guide to Pacific coast fishes of North America. Houghton Mifflin Co., Boston, Massachusetts, USA

Fetterer F, Knowles K, Meier W, Savoie M (2002, updated 2008) Sea Ice Index. Boulder, Colorado USA: National Snow and Ice Data Center. Digital media

Fortier L, Sirois P, Michaud J, Barber D (2006) Survival of Arctic cod larvae (*Boreogadus saida*) in relation to sea ice and temperature in the Northeast Water Polynya (Greenland Sea). Can J Fish Aquat Sci 63:1608-1616

Fry B, Cieri M, Hughes J, Tobias C, Deegan LA, Peterson B (2008) Stable isotope monitoring of benthic-planktonic coupling using salt marsh fish. Mar Ecol Prog Ser 369:193-204

Fry B, Sherr EB (1984) $\delta^{13}C$ Measurements as indicators of carbon flow in marine and freshwater ecosystems. Contrib Mar Sci 27:13-47

Gauch HG Jr (1982) Multivariate analysis in community ecology. Cambridge University Press, New York, New York, USA

Gillispie JG, Smith RL, Barbour E, Barber WE (1997) Distribution, abundance, and growth of arctic cod in the northeastern Chukchi Sea. Am Fish Soc Symp 19:81-89

Gradinger R, Bluhm B (2004) In-situ observations on the distribution and behaviour of amphipods and Arctic cod (*Boreogadus saida*) under the sea ice of the High Arctic Canada Basin. Polar Biol 27:595-603

Grebmeier JM, Barry JP (1991) The influence of oceanographic processes on pelagic-benthic coupling in polar regions: A benthic perspective. J Mar Syst 2: 495-518

Grebmeier JM, Barry JP (2007) Benthic processes in polynyas. In: Smith WO Jr, Barber DG (eds) Polynyas: Windows to the World. Elsevier Oceanography Series, 74:363-390

Grebmeier JM, Cooper LW (1995) Influence of the St. Lawrence Island polynya upon the Bering Sea benthos. J Geophy Res 100:4439-4460

Grebmeier JM, Cooper LW, Feder HM, Sirenko BI (2006a) Ecosystem dynamics of the Pacific-Influenced northern Bering and Chukchi Seas. Prog Oceanogr 71: 331-361

Grebmeier JM, Dunton KH (2000) Benthic processes in the northern Bering Sea/Chukchi Seas: status and global changes. In: Huntington HP (ed) Impacts of changes in sea ice and other environmental parameters in the Arctic. Report of the Marine Mammal Commission workshop, 15-17 February 2000, Girdwood, Alaska, USA

Grebmeier JM, Feder HM, McRoy CP (1989) Pelagic-benthic coupling on the shelf of the northern Bering and Chukchi Seas. II. Benthic community structure. Mar Ecol Prog Ser 51:253-268

Grebmeier JM, McRoy CP, Feder HM (1988) Pelagic-benthic coupling on the shelf of the northern Bering and Chukchi Seas. I. Food supply source and benthic biomass. Mar Ecol Prog Ser 48:57-67

Grebmeier JM, Overland JE, Moore SE, Farley EV, Carmack EC, Cooper LW, Frey KE, Helle JH, McLaughlin FA, McNutt SL (2006b) A major ecosystem shift in the northern Bering Sea. Science 311:1461-1464

Helle J, Farley E, Murphy J, Feldmann A, Cieciel K, Moss J, Eisner L, Pohl J, Courtney M (2007) The Bering-Aleutian salmon international survey (BASIS). AFSC quarterly report feature (January-February-March 2007)

Higgins JJ (2004) Introduction to modern nonparametric statistics. Brook/Cole-Thomson Learning, Pacific Grove, California, USA

Hintze J (2009) NCSS, LLC. Kaysville, Utah. www.ncss.com

Hobson KA, Welch HE (1992) Determination of trophic relationships within a high Arctic marine food web using $\delta^{13}C$ and $\delta^{15}N$ analysis. Mar Ecol Prog Ser 84:9-18

Hop H, Welch HE, Crawford RE (1997) Population structure and feeding ecology of Arctic cod schools in the Canadian High Arctic. Am Fish Soc Symp 19:68-80

Hunt GL Jr, Stabeno P, Walters G, Sinclair E, Brodeur RD, Napp JM, Bond NA (2002) Climate change and control of the southeastern Bering Sea pelagic ecosystem. Deep Sea Res II 49:5821-5853

Kling GW, Fry B, O'Brien WJ (1992) Stable isotopes and planktonic trophic structure in arctic lakes. Ecology 73:561-566

Lawlor LR (1980) Overlap, similarity, and competition coefficients. Ecology 61(2):245-251

Lee RF (1974) Lipid composition of the copepod *Calanus hyperboreas* from the Arctic Ocean. Change with depth and season. Mar Bio 26:313-318

Legendre L, Ackley SF, Deickmann GS, Gulliksen B, Horner R, Hoshiai T, Melnikov IA, Reeburgh WS, Spindler M, Sullivan CW (1992) Ecology of sea ice biota. 2. Global significance. Polar Biol 12:429-444

Lesage V, Hammill MO, Kovacs KM (2001) Marine mammals and the community structure of the estuary and gulf of St Lawrence, Canada: evidence from stable isotope analysis. Mar Ecol Progr Ser 210:203-221

Linton RL, Davies RW, Wrona FJ (1981) Resource utilization indices; an assessment. J Anim Ecol 50:283-293

Litzow MA, Bailey KM, Prahl FG, Heintz R (2006) Climate regime shifts and reorganization of fish communities: the essential fatty acid limitation hypothesis. Mar Ecol Prog Ser 315:1-11

Lonne OJ, Gulliksen B (1989) Size, age and diet of polar cod, *Boreogadus saida* (Lepechin 1773), in ice covered waters. Polar Biol 9:187-191

Loughlin TR, Sukhanova IN, Sinclair EH, Ferrero RC (1999) Summary of biology and ecosystem dynamics in the Bering Sea. In: Loughlin TR, Ohtani K (eds.) Dynamics of the Bering Sea. University of Alaska Sea Grant, Fairbanks, Alaska, p387-407

Lovvorn JR, Cooper LW, Brooks ML, De Ruyck CC, Bump JK, Grebmeier JM (2005) Organic matter pathways to zooplankton and benthos under pack ice in late winter and open water in late summer in the north-central Bering Sea. Mar Ecol Prog Ser 291:135-150

Lowry LF, Frost KJ (1981) Distribution, growth, and the foods of Arctic cod (*Boreogadus saida*) in the Bering, Chukchi, and Beaufort Seas. Can Field-Nat 95:186-191

Lønne OJ, Gulliksen B (1989) Size, age and diet of Polar cod, *Boreogadus saida* (Lepechin 1773), in ice covered waters. Polar Biol 9:187-191

McConnaughey T, McRoy CP (1979) Food web structure and the fractionation of carbon isotopes in the Bering Sea. Mar Bio 53:257-262

McConnaughey RA, Smith KR (2000) Association between flatfish abundance and surficial sediments in the eastern Bering Sea. Can J Fish Aquat Sci 57:2410-2419

Mecklenburg CW, Mecklenburg TA, Thorsteinson LK (2002) Fishes of Alaska. American Fisheries Society, Bethesda, Maryland, USA

Michener RH, Schell DM (1994) Stable isotope ratios as tracers in marine aquatic food webs. In: Lajtha K, Michener RH (eds) Stable isotopes in ecology and environmental science. Blackwell Scientific Publications, Oxford London Edinburgh Boston Melbourne Paris Berlin Vienna, p137-157

Minagawa M. Wada E (1984) Stepwise enrichment of $\delta^{15}N$ along food chains: Further evidence and the relation between $\delta^{15}N$ and animal age. Geochim Cosmochim Ac 48:1135-1140

Moore SE, Grebmeier JM, Davies JR (2003) Gray whale distribution relative to forage habitat in the northern Bering Sea: current conditions and retrospective summary. Can J Zool 81:734-742

Morales Maqueda MA, Willmott AJ, Biggs NRT (2004) Polynya dynamics: a review of observations and modeling. Rev Geophysics 42:1-37

Mueter FJ, Litzow MA (2008) Sea ice retreat alters the biogeography of the Bering Sea continental shelf. Ecol Appl 18:309-320

Mueter FJ, Norcross BL (2002) Spatial and temporal patterns in the demersal fish community on the shelf and upper slope regions of the Gulf of Alaska. Fish Bull 100:559-581

Naidu AS, Cooper LW, Finney BP, Macdonald RW, Alexander C, Semiletov IP (2000) Organic carbon isotope ratios ($\delta^{13}C$) of Arctic Amerasian continental shelf sediments. Int J Earth Sci 89:522-531

Nicolas D, Loc'h FL, Désaunay Y, Hamon D, Blanchet A, Le Pape O (2007) Relationships between benthic macrofauna and habitat suitability for juvenile common sole (Solea solea, L.) in the Vilaine estuary (Bay of Biscay, France) nursery ground. Estuar Coast Shelf Sci 73:639-650

Nihoul JCJ, Adam P, Brasseur P, Deleersnijder E, Djenidi S, Haus J (1993) Three-dimensional general circulation model of the Northern Bering Sea's summer ecohydrodynamics. Cont Shelf Res 13:509-542

Overland JE, Stabeno PJ (2004) Is the climate of the Bering Sea warming and affecting the ecosystem? EOS Trans Am Geophys Union 85: 309-312

Perry AL, Low PJ, Ellis JR, Reynolds JD (2005) Climate change and distribution shifts in marine fishes. Science 308:1912-1915

Pirtle-Levy R (2006) A shelf-to-basin examination of food supply for arctic benthic macrofauna and the potential biases of sampling methodology. Masters Thesis, University of Tennessee, Knoxville, TN, USA. Available at http://etd.utk.edu/2006/Pirtle-LevyRebecca.pdf

Post (2002) Using stable isotopes to estimate trophic position: models, methods and assumptions. Ecology 83:703-718

Post DM, Layman CA, Arrington DA, Takimoto G, Quattrochi J, Montana CG (2007) Getting to the fat of the matter: models, methods and assumptions for dealing with lipids in stable isotope analyses. Oecologia 152:179-189

Rau GH, Mearns AJ, Young DR, Olson RJ, Schafer HA, Kaplan IR (1983) Animal $^{13}C/^{12}C$ correlates with trophic level in pelagic food webs. Ecology 64:1314-1318

Rau GH, Sweeney RE, Kaplan IR (1982) Plankton $^{13}C:^{12}C$ ratio changes with latitude: Differences between northern and southern oceans. Deep Sea Res 29:1035-1039

Reuter RF, TenBrink TT (2008) Assessment of sculpin stocks in the Bering Sea/Aleutian Islands. In: The plan team for the groundfish fisheries of the Bering Sea and Aleutian Islands (eds) Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands regions. North Pacific Fishery Management Council, Anchorage, Alaska, p 1411 http://www.afsc.noaa.gov/refm/docs/2008/BSAIsculpin.pdf

Schell DM, Barnett BA, Vinette KA (1998) Carbon and nitrogen isotope ratios in zooplankton of the Bering, Chukchi and Beaufort Seas. Mar Ecol Prog Ser 162:11-23

Schumacher JD, Aagaard K, Pease CH, Tripp RB (1983) Effects of a shelf polynya on flow and water properties in the northern Bering Sea. J Geophys Res 88:2723-2732

Scott JS (1982) Selection of bottom type by groundfishes of the Scotian Shelf. Can J Fish Aquat Sci 39:943-947

Serreze MC, Holland MM, Stroeve J (2007) Perspectives on the Arctic's shrinking sea-ice cover. Science 315:1533-1536

Skud BE (1982) Dominance in fishes: The relation between environment and abundance. Science 216:144-149

Smith RL, Vallarino M, Barbour E, Fitzpatrick E, Barber WE (1997) Population biology of the Bering flounder in the northeastern Chukchi Sea. Am Fish Soc Symp 19:127-132

Søreide JE, Hop H, Carroll ML, Falk-Petersen S, Hegseth EN (2006) Seasonal food web structures and sympagic-pelagic coupling in the European Arctic revealed by stable isotopes and a two-source food web model. Prog Oceanogr 71:59-87

Spencer PD (2008) Density-indepdendent and density-dependent factors affecting temporal changes in spatial distributions of eastern Bering Sea flatfish. Fish Oceanogr 17:396-410

Springer AM, McRoy CP, Flint MV (1996) Review: The Bering Sea Green Belt: shelf-edge processes and ecosystem production. Fish Oceanogr 5:205-223

Stabeno PJ, Overland JE (2001) Bering Sea shifts toward an earlier spring transition. EOS Trans Am Geophys Union 82:317-321

Sweeting CJ, Polunin NVC, Jennings S (2006) Effects of chemical lipid extraction and arithmetic lipid correction on stable ratios of fish tissues. Rapid Commun Mass Spectrom 20:595-601

Tamelander T, Renaud PE, Hop H, Carroll ML, Ambrose WG Jr., Hobson KA (2006). Trophic relationships and pelagic-benthic coupling during summer in the Barent Sea Marginal Ice Zone, revealed by stable carbon and nitrogen isotope measurements. Mar Ecol Prog Ser 310:33-46

Tremblay C, Runge JA, Legendre L (1989). Grazing and sedimentation of ice algae during and immediately after a bloom at the ice water interface. Mar Ecol Prog Ser 56:291-300

Tynan C, DeMaster DP (1997) Observations and predictions of Arctic climate change: potential effects on marine mammals. Arctic 50:308-322

Vander Zanden MJ, Rasmussen JB (2001) Variation in δ^{15}N and δ^{13}C trophic fractionation: Implications for aquatic food web studies. Limnol Oceanogr 46:2061-2066

Walsh JJ, McRoy CP, Coachman LK, Goering JJ, Nihoul JJ, Whiteledge TE, Blackburn TH, Parker PL, Wirick CD, Shuert PG, Grebmeier JM, Springer AM, Tripp RD, Hansell DA, Djenidi S, Deleersnijder E, Henriksen K, Lund BA, Andersen P, Muller-Karger FE, Dean K (1989) Carbon and nitrogen cycling within the Bering/Chukchi Seas: Source regions for organic matter effecting AOU demands of the Arctic Ocean. Prog Oceanogr 22:277-359

Warburton K, Blaber SJM (1992) Patterns of recruitment and resource use in a shallow-water fish assemblage in Moreton Bay, Queensland. Mar Ecol Prog Ser 90:113-126

Welch HE, Bergmann MA, Siferd TD, Martin KA, Curtis MF, Crawford RE, Conover RJ, Hop H (1992) Energy flow through the marine ecosystem of Lancaster Sound region, Arctic Canada. Arctic 45:343-357

Wyllie-Echeverria T, Ohtani K (1999) Seasonal sea ice variability and the Bering Sea Ecosystem. In: Loughlin TR, Ohtani K (eds) Dynamics of the Bering Sea. University of Alaska Sea Grant, Fairbanks, Alaska, USA, p435-451

Wyllie-Echeverria T, Wooster WS (1998) Year-to-year variations in Bering Sea ice cover and some consequences for fish distributions. Fish Oceanogr 7:159-170

Zaret TM, Rand AS (1971) Competition in tropical stream fishes: support for the competitive exclusion principle. Ecology 52:336-342

Appendices

Appendix A. Station information for all sites trawled during USCGC *Healy* cruises 2006 (HLY0601) and 2007 (HLY0702)

Cruise	Station Number	Station Name	Date MM/DD/YYYY	Latitude (°N)	Longitude (°W)	Depth (m)	Bottom Water Temperature (°C)
HLY0601	1	NEC5	5/9/2006	61.389	-171.947	62	-1.69
HLY0601	2	SEC5	5/9/2006	61.564	-172.899	66	-1.70
HLY0601	3	SIL5	5/10/2006	61.720	-173.604	62	-1.73
HLY0601	4	SWC5	5/10/2006	61.887	-174.375	67	-1.72
HLY0601	6	NWC5	5/10/2006	62.053	-175.190	75	-1.73
HLY0601	7	DLN5	5/11/2006	62.166	-176.011	95	-0.25
HLY0601	8	NWC4	5/11/2006	62.399	-174.583	68	-1.69
HLY0601	11	SWC4	5/12/2006	62.262	-173.713	62	-1.65
HLY0601	12	SIL4	5/12/2006	62.079	-172.946	60	-1.69
HLY0601	13	SEC4	5/12/2006	61.938	-172.224	57	-1.56
HLY0601	14	NEC4	5/13/2006	61.783	-171.297	47	-1.50
HLY0601	15	SIL3	5/13/2006	62.440	-172.318	53	-1.75
HLY0601	16	POP4	5/13/2006	62.403	-172.690	58	-1.73
HLY0601	17	SWC4A	5/13/2006	62.428	-173.404	63	-1.69
HLY0601	18	SWC3	5/14/2006	62.581	-173.086	67	-1.71
HLY0601	19	VNG3.5	5/14/2006	62.574	-173.559	60	-1.75
HLY0601	20	CD1	5/14/2006	62.678	-173.390	64	-1.77
HLY0601	21	VNG4	5/14/2006	62.755	-173.426	69	-1.75
HLY0601	22	NWC3	5/15/2006	62.783	-173.873	72	-1.75
HLY0601	23	DLN3	5/15/2006	62.902	-174.577	65	-1.72
HLY0601	29	SWC3A	5/17/2006	62.752	-172.683	58	-1.73
HLY0601	30	POP3A	5/17/2006	62.571	-172.298	51	-1.75
HLY0601	31	SEC2.5	5/17/2006	62.496	-171.841	48	-1.65
HLY0601	32	SEC3	5/18/2006	62.286	-171.569	47	-1.50

Appendix A. Continued

Cruise	Station Number	Station Name	Date MM/DD/YYYY	Latitude (°N)	Longitude (°W)	Depth (m)	Bottom Water Temperature (°C)
HLY0601	36	SEC2	5/18/2006	62.612	-170.919	45	-1.44
HLY0601	37	SIL2	5/19/2006	62.752	-171.672	50	-1.76
HLY0601	39	VNG5	5/19/2006	62.963	-172.978	67	-1.72
HLY0601	40	NWC2	5/19/2006	63.118	-173.116	69	-1.71
HLY0601	44	KIV1	5/20/2006	64.234	-170.864	35	-1.44
HLY0601	46	KIV3	5/20/2006	64.134	-169.354	38	-1.12
HLY0601	50	NOM4	5/21/2006	64.351	-168.629	40	-1.29
HLY0601	51	NOM3	5/21/2006	64.394	-169.279	41	-0.94
HLY0601	53	NOM1	5/22/2006	64.474	-170.831	43	-1.42
HLY0601	54	RUS1	5/22/2006	64.685	-170.566	49	-1.38
HLY0601	55	RUS2	5/22/2006	64.658	-169.934	46	-1.36
HLY0601	59	KNG1	5/23/2006	64.953	-169.855	47	-1.54
HLY0601	60	CPW1	5/23/2006	65.189	-169.664	46	-1.50
HLY0601	61	KNG2	5/24/2006	64.997	-169.134	48	-1.45
HLY0601	63	KNG3	5/24/2006	64.989	-168.411	47	-1.40
HLY0601	64	CPW3	5/24/2006	65.191	-168.391	48	-1.45
HLY0601	83	NEC1	5/27/2006	62.750	-169.588	42	-1.27
HLY0601	84	SEC1	5/27/2006	62.987	-170.261	30	-1.31
HLY0601	85	SEC2	5/27/2006	62.613	-170.943	45	-1.56
HLY0601	86	NEC5A	5/28/2006	61.408	-171.996	60	-1.67
HLY0601	87	SEC4	5/28/2006	61.938	-172.212	58	-1.22
HLY0601	88	SIL4	5/28/2006	62.077	-172.944	57	-1.49
HLY0601	89	POP4	5/28/2006	62.403	-172.690	58	-1.67
HLY0601	90	SWC3A	5/29/2006	62.757	-172.711	63	-1.72
HLY0601	96	VNG5	5/29/2006	62.973	-173.021	70	-1.67
HLY0601	97	NWC2.5	5/30/2006	63.026	-173.469	71	-1.71
HLY0601	98	NWC2	5/30/2006	63.104	-173.136	73	-1.70

Appendix A. Continued

Cruise	Station Number	Station Name	Date MM/DD/YYYY	Latitude (°N)	Longitude (°W)	Depth (m)	Bottom Water Temperature (°C)
HLY0601	104	VNG4	5/31/2006	62.756	-173.426	70	-1.71
HLY0601	105	CD1	5/31/2006	62.679	-173.377	67	-1.69
HLY0601	106	SWC4A	5/31/2006	62.414	-173.421	63	-1.73
HLY0601	107	VNG3.5	6/1/2006	62.570	-173.592	67	-1.73
HLY0601	108	NWC3	6/1/2006	62.780	-173.850	73	-1.72
HLY0601	109	DLN3	6/1/2006	62.899	-174.552	80	-1.69
HLY0601	110	NWC4	6/1/2006	62.396	-174.545	71	-1.65
HLY0601	111	NWC5	6/1/2006	62.060	-175.207	80	-1.71
HLY0601	112	VNG1	6/2/2006	62.024	-175.065	80	-1.69
HLY0702	1	NEC5	5/18/2007	61.389	-171.951	62	-1.75
HLY0702	6	NWC5	5/19/2007	62.063	-175.207	82	-1.65
HLY0702	7	DLN5	5/20/2007	62.148	-176.028	96	-1.68
HLY0702	8	DLN4	5/20/2007	62.513	-175.296	81	-1.76
HLY0702	9	NWC4	5/20/2007	62.135	-175.979	74	-1.75
HLY0702	12	VNG3.5	5/21/2007	61.922	-172.159	67	-1.74
HLY0702	13	SWC4A	5/21/2007	62.412	-173.434	63	-1.74
HLY0702	14	SWC4	5/21/2007	62.243	-173.743	65	-1.72
HLY0702	15	SIL4	5/21/2007	62.081	-172.940	58	-1.69
HLY0702	16	SEC4	5/21/2007	61.929	-172.215	58	-1.65
HLY0702	17	NEC4	5/22/2007	61.771	-171.314	57	-1.72
HLY0702	18	NEC3	5/22/2007	62.057	-170.625	50	-1.49
HLY0702	19	SEC3	5/22/2007	62.277	-171.565	47	-1.61
HLY0702	20	SEC2.5	5/23/2007	62.500	-171.848	50	-1.69
HLY0702	21	POP3A	5/23/2007	62.567	-172.290	51	-1.66
HLY0702	22	SIL3	5/23/2007	62.431	-172.316	52	-1.65
HLY0702	23	POP4	5/23/2007	62.399	-172.696	60	-1.68
HLY0702	24	SWC3	5/23/2007	62.578	-173.086	65	-1.73

Appendix A. Continued

Cruise	Station Number	Station Name	Date MM/DD/YYYY	Latitude (°N)	Longitude (°W)	Depth (m)	Bottom Water Temperature (°C)
HLY0702	25	CD1	5/24/2007	62.501	-171.850	68	-1.73
HLY0702	26	VNG4	5/24/2007	62.749	-173.411	70	-1.73
HLY0702	27	NWC3	5/24/2007	62.782	-173.886	74	-1.74
HLY0702	28	DLN3	5/24/2007	62.896	-174.587	80	-1.72
HLY0702	30	NWC2.5	5/25/2007	63.040	-173.438	72	-1.69
HLY0702	31	NWC2	5/25/2007	63.110	-173.175	70	-1.55
HLY0702	33	SWC3A	5/26/2007	62.753	-172.712	62	-1.68
HLY0702	35	SIL2	5/26/2007	62.755	-171.674	51	-1.46
HLY0702	36	SEC2	5/26/2007	62.608	-170.949	46	-1.57
HLY0702	37	NEC2.5	5/26/2007	62.471	-170.965	44	-1.41
HLY0702	38	NEC2	5/27/2007	62.429	-170.057	38	-1.05
HLY0702	56	KIV1	5/29/2007	64.225	-170.858	36	-0.61
HLY0702	58	KIV3	5/29/2007	64.126	-169.341	38	0.42
HLY0702	59	KIV4	5/29/2007	64.066	-168.618	36	0.20
HLY0702	60	KIV5	5/30/2007	64.019	-167.874	40	-0.41
HLY0702	61	NOM5	5/30/2007	64.361	-168.033	37	-1.39
HLY0702	62	NOM4	5/30/2007	64.364	-168.644	41	0.46
HLY0702	63	NOM3	5/31/2007	64.379	-169.286	40	0.38
HLY0702	66	RUS1	5/31/2007	64.692	-170.588	49	0.06
HLY0702	67	RUS2	5/31/2007	64.662	-169.941	47	-0.42
HLY0702	68	RUS3	6/1/2007	64.676	-169.102	48	0.23
HLY0702	70	KNG3	6/1/2007	65.013	-168.420	48	0.57
HLY0702	71	RUS4A	6/1/2007	64.805	-169.026	46	0.47
HLY0702	72	KNG2	6/2/2007	64.991	-169.139	50	0.46
HLY0702	73	KNG1	6/2/2007	64.955	-169.886	44	-0.14
HLY0702	74	CPW1	6/2/2007	65.182	-169.662	45	-0.20
HLY0702	75	CPW2	6/2/2007	65.176	-169.042	52	0.51

Appendix A. Continued

Cruise	Station Number	Station Name	Date MM/DD/YYYY	Latitude (°N)	Longitude (°W)	Depth (m)	Bottom Water Temperature (°C)
HLY0702	76	CPW3	6/3/2007	65.182	-168.393	50	0.34
HLY0702	109	NWC2	6/6/2007	63.115	-173.137	71	-0.26
HLY0702	110	VNG5	6/6/2007	62.971	-172.979	66	-1.63
HLY0702	111	NWC2.5	6/6/2007	63.028	-173.432	72	-1.63
HLY0702	113	VNG4	6/7/2007	62.752	-173.401	70	-1.68
HLY0702	114	CD1	6/7/2007	62.674	-173.360	68	-1.72
HLY0702	115	VNG3.5	6/7/2007	62.570	-173.567	68	-1.73
HLY0702	116	SWC3	6/7/2007	62.579	-173.079	63	-1.73
HLY0702	118	SEC2.5	6/8/2007	62.492	-171.838	49	-1.59
HLY0702	120	NEC2.5	6/8/2007	62.470	-170.957	45	-1.25
HLY0702	121	NEC2	6/9/2007	62.431	-170.064	39	-1.08
HLY0702	137	NEC3	6/10/2007	62.055	-170.632	49	-1.31
HLY0702	138	SEC4	6/11/2007	61.927	-172.214	57	-1.51
HLY0702	139	SEC5	6/11/2007	61.565	-172.921	70	-1.67
HLY0702	140	SIL5	6/11/2007	61.725	-173.616	70	-1.67
HLY0702	141	SWC5	6/11/2007	61.892	-174.364	77	-1.72
HLY0702	142	VNG1	6/11/2007	62.019	-175.062	80	-1.60
HLY0702	143	NWC5	6/12/2007	62.052	-175.198	83	-1.61
HLY0702	144	DLN5	6/12/2007	62.147	-176.023	95	-1.70
HLY0702	145	DLN4	6/12/2007	62.512	-175.300	80	-1.74
HLY0702	146	NWC4	6/12/2007	62.389	-174.552	71	-1.73

Appendix B. Environmental variables for trawl stations occuppied during USCGC *Healy* cruises 2006 (HLY0601) and 2007 (HLY0702). Key: BW Salinity (bottom water salinity), Si (bottom water silicate), N (bottom water nitrite and nitrate), PO4 (bottom water phosphate), NH4 (bottom water ammonium), BW Chl *a* (bottom water chlorophyll *a*), Int Chl *a* (integrated water column chlorophyll *a*), Sed Chl *a* (chlorophyll *a* in surface sediments), Sed Size (surface sediment grain size), TOC (total organic carbon of surface sediments), TON (total organic nitrogen of surface sediments), and C/N (surface sediments C/N)

Cruise	**Station Number**	**Station Name**	**BW Salinity**	**Si** (μmol L^{-1})	**N** (μmol L^{-1})	**PO4** (μmol L^{-1})	**NH4** (μmol L^{-1})	**BW Chl *a*** (mg m^{-3})	**Int Chl *a*** (mg m^{-2})	**Sed Chl *a*** (mg m^{-2})	**Sed size** (phi)	**TOC (%)**	**TON (%)**	**C/N** (wt/wt)
HLY0601	3	SIL5	31.88	22.44	6.71	1.28	2.93	0.04	45.86	7.50	5	0.95	0.14	6.98
HLY0601	6	NWC5	32.01	21.06	5.63	1.09	2.72	0.32	69.05	5.76	5	1.07	0.15	6.98
HLY0601	7	DLN5	32.33	53.05	19.07	2.06	0.42	0.21	10.28	8.86	5	1.76	0.27	6.64
HLY0601	8	NWC4	31.95	24.97	5.63	1.37	3.08	0.46	23.88	6.22	5	0.99	0.16	6.29
HLY0601	11	SWC4	31.65	20.86	4.49	1.21	2.71	0.57	54.49	5.03	4	0.41	0.05	7.98
HLY0601	12	SIL4	31.66	16.42	3.04	0.88	2.96	0.86	87.26	8.01	4	0.50	0.07	7.05
HLY0601	13	SEC4	31.53	16.94	4.07	1.10	2.73	0.25	10.59	8.28	5	0.46	0.07	7.09
HLY0601	14	NEC4	31.41	13.70	2.34	0.99	2.95	0.36	17.75	10.51	5	0.71	0.10	7.45
HLY0601	15	SIL3	32.35	21.95	3.64	1.05	0.92	9.88	428.45	5.26	4	0.27	0.03	8.32
HLY0601	16	POP4	32.26	20.16	2.92	1.02	0.83	11.04	320.09	7.56	5	0.76	0.11	6.78
HLY0601	17	SWC4A	31.68	9.88	2.33	0.66	2.79	0.79	177.59	7.40	5	0.72	0.11	6.48
HLY0601	18	SWC3	31.98	26.66	5.24	1.38	2.91	1.96	274.32	10.65	5	1.11	0.17	6.38
HLY0601	19	VNG3.5	32.30	31.43	6.36	1.62	2.28	6.60	355.20	11.04	5	1.12	0.16	6.87

Appendix B. Continued

Cruise	**Station Number**	**Station Name**	**BW Salinity**	**Si** (μmol L^{-1})	**N** (μmol L^{-1})	**PO4** (μmol L^{-1})	**NH4** (μmol L^{-1})	**BW Chl *a*** (mg m^{-3})	**Int Chl *a*** (mg m^{-2})	**Sed Chl *a*** (mg m^{-2})	**Sed size** (phi)	**TOC (%)**	**TON (%)**	**C/N** (wt/wt)
HLY0601	20	CD1	32.55	27.30	5.33	1.30	1.79	13.24	562.70	13.18	5	1.37	0.22	6.26
HLY0601	21	VNG4	32.46	32.61	6.75	1.47	1.94	9.24	528.97	8.86	5	1.48	0.24	6.1
HLY0601	22	NWC3	32.30	31.02	6.80	1.41	1.89	5.24	348.36	8.31	5	1.50	0.25	6.08
HLY0601	23	DLN3	32.13	35.97	11.27	1.70	1.67	1.10	587.23	12.01	5	1.59	0.25	6.48
HLY0601	29	SWC3A	32.45	31.54	5.66	1.58	2.57	7.80	502.60	4.55	5	0.79	0.11	6.97
HLY0601	30	POP3A	32.47	26.47	5.41	1.59	1.67	8.48	702.01	10.26	4	0.46	0.07	6.55
HLY0601	31	SEC2.5	31.94	17.10	2.73	1.24	1.60	7.28	579.43	9.32	4	2.60	0.65	4
HLY0601	36	SEC2	32.01	5.64	0.96	0.80	0.67	10.00	532.94	8.21	4	0.53	0.08	6.64
HLY0601	37	SIL2	32.44	28.85	5.84	1.43	2.11	6.56	621.82	10.16	5	0.61	0.10	6.25
HLY0601	39	VNG5	32.65	27.35	5.29	1.28	2.42	6.72	759.73	13.39	5	0.84	0.14	6.08
HLY0601	40	NWC2	32.69	23.42	3.57	1.18	0.70	7.76	613.81	16.10	5	1.27	0.21	6.13
HLY0601	44	KIV1	32.03	28.78	7.35	1.32	0.49	20.28	575.08	8.11	2	0.09	0.01	6.68
HLY0601	46	KIV3	32.13	29.72	6.92	1.30	0.46	12.72	411.79	13.28	4	0.23	0.04	6.44
HLY0601	50	NOM4	32.15	10.80	2.07	1.18	0.50	22.48	724.12	17.85	3	0.28	0.04	6.96
HLY0601	51	NOM3	32.19	8.80	3.55	1.10	0.50	23.40	759.22	7.48	3	0.28	0.04	6.2
HLY0601	54	RUS1	32.24	36.51	11.08	1.43	0.58	15.00	673.20	26.46	5	0.71	0.12	5.84
HLY0601	55	RUS2	32.16	30.45	8.07	1.24	1.00	16.92	807.29	21.04	3	0.49	0.08	6.35
HLY0601	59	KNG1	32.42	32.73	9.66	1.46	0.46	14.56	793.19	9.03	4	0.35	0.06	6.38

Appendix B. Continued

Cruise	**Station Number**	**Station Name**	**BW Salinity**	**Si** (µmol L^{-1})	**N** (µmol L^{-1})	**PO4** (µmol L^{-1})	**NH4** (µmol L^{-1})	**BW Chl *a*** (mg m^{-3})	**Int Chl *a*** (mg m^{-2})	**Sed Chl *a*** (mg m^{-2})	**Sed size** (phi)	**TOC (%)**	**TON (%)**	**C/N** (wt/wt)
HLY0601	60	CPW1	32.88	18.51	6.96	1.09	1.14	12.28	789.30	17.76	3	0.37	0.07	5.1
HLY0601	61	KNG2	32.35	22.74	6.36	1.36	2.37	21.92	1053.99	19.58	3	0.20	0.03	5.71
HLY0601	63	KNG3	32.27	19.84	5.18	1.46	3.59	16.92	833.80	2.62	3	0.23	0.04	6.35
HLY0601	64	CPW3	32.33	18.88	7.18	1.20	3.99	13.20	557.73	8.64	3	0.44	0.06	6.89
HLY0601	83	NEC1	32.30	0.01	0.42	0.01	0.17	9.72	402.29	15.97	3	0.34	0.05	6.68
HLY0601	85	SEC2	32.25	23.65	4.68	1.34	2.16	3.68	114.29	15.62	4	0.43	0.06	7.51
HLY0601	88	SIL4	31.64	23.84	4.70	1.27	3.27	1.35	297.73	8.67	5	0.57	0.08	6.9
HLY0601	89	POP4	32.15	25.17	4.96	1.35	2.92	12.68	339.15	15.68	5	0.70	0.10	7.34
HLY0601	96	VNG5	32.30	24.01	6.20	1.25	3.45	7.88	770.83	10.88	5	1.78	0.30	5.87
HLY0601	97	NWC2.5	32.11	30.08	7.12	1.52	3.19	6.80	750.58	14.25	5	1.70	0.28	6.03
HLY0601	98	NWC2	32.13	30.97	9.27	1.51	2.54	7.72	753.13	15.97	5	1.27	0.21	6.13
HLY0601	104	VNG4	32.18	25.91	6.50	1.25	2.36	6.08	443.74	14.12	5	1.48	0.25	5.99
HLY0601	105	CD1	32.41	21.93	5.23	1.22	3.03	7.44	429.02	13.25	5	1.22	0.21	5.89
HLY0601	106	SWC4A	32.34	27.88	6.95	1.35	4.00	5.84	371.43	11.53	5	0.94	0.14	6.51
HLY0601	107	VNG3.5	32.34	25.59	7.32	1.31	3.30	5.28	337.54	18.38	5	1.36	0.22	6.18
HLY0601	109	DLN3	32.11	32.84	10.96	1.49	2.37	5.64	586.52	14.61	5	1.60	0.25	6.32
HLY0601	110	NWC4	31.89	28.35	7.12	1.45	3.54	4.52	473.09	16.92	5	0.97	0.15	6.59
HLY0601	111	NWC5	31.99	27.94	7.32	1.40	3.75	1.74	374.65	14.48	5	1.09	0.17	6.42

Appendix B. Continued

Cruise	Station Number	Station Name	BW Salinity	Si (μmol L^{-1})	N (μmol L^{-1})	PO4 (μmol L^{-1})	NH4 (μmol L^{-1})	BW Chl *a* (mg m^{-3})	Int Chl *a* (mg m^{-2})	Sed Chl *a* (mg m^{-2})	Sed size (phi)	TOC (%)	TON (%)	C/N (wt/wt)
HLY0601	112	VNG1	31.95	20.21	6.46	1.14	3.38	2.40	449.64	9.61	5	1.01	0.16	6.26
HLY0702	1	NEC5	32.58	34.03	13.52	1.69	4.33	1.77	294.54	7.31	5	0.75	0.10	7.52
HLY0702	6	NWC5	32.37	41.10	12.24	1.94	3.30	2.07	587.31	6.95	5	1.02	0.14	7.07
HLY0702	7	DLN5	32.52	36.01	10.55	1.79	2.63	1.24	476.81	8.77	5	1.88	0.27	6.85
HLY0702	8	DLN4	32.62	31.85	12.31	1.68	2.79	1.05	246.77	9.58	5	1.00	0.17	5.87
HLY0702	12	VNG3.5	32.81	40.65	13.75	1.92	3.34	3.13	327.08	14.68	5	1.15	0.16	7.05
HLY0702	13	SWC4A	32.81	47.36	15.29	2.09	2.02	0.51	444.30	11.07	5	0.96	0.13	7.69
HLY0702	14	SWC4	32.70	44.95	14.74	2.01	2.00	5.40	429.04	16.01	4	0.50	0.05	9.37
HLY0702	15	SIL4	32.59	41.78	14.12	1.93	2.90	6.28	361.78	17.37	4	0.78	0.11	7.33
HLY0702	16	SEC4	32.54	28.72	8.81	1.60	2.34	6.00	237.70	16.79	5	0.53	0.07	7.85
HLY0702	17	NEC4	32.55	25.05	6.82	1.62	3.58	5.20	221.99	7.57	5	0.54	0.07	8.00
HLY0702	20	SEC2.5	32.81	28.43	8.65	1.51	1.74	6.80	147.72	25.06	4	0.39	0.06	6.17
HLY0702	21	POP3A	32.84	31.91	11.74	1.79	2.44	7.60	343.34	18.83	4	0.45	0.07	6.82
HLY0702	23	POP4	32.85	29.89	9.63	1.64	2.35	5.04	249.43	13.90	5	0.85	0.14	5.97
HLY0702	24	SWC3	32.83	28.33	10.13	1.59	2.52	5.28	310.67	30.65	5	1.06	0.16	6.61
HLY0702	25	CD1	32.80	35.71	13.05	1.76	2.14	2.17	309.50	27.08	5	1.34	0.22	5.99
HLY0702	26	VNG4	32.74	42.49	13.85	2.05	2.16	2.74	306.26	29.09	5	1.48	0.23	6.30
HLY0702	27	NWC3	32.78	37.14	12.81	1.92	1.67	3.49	402.15	10.88	5	1.84	0.30	6.19

Appendix B. Continued

Cruise	Station Number	Station Name	BW Salinity	Si (μmol L^{-1})	N (μmol L^{-1})	PO4 (μmol L^{-1})	NH4 (μmol L^{-1})	BW Chl *a* (mg m^{-3})	Int Chl *a* (mg m^{-2})	Sed Chl *a* (mg m^{-2})	Sed size (phi)	TOC (%)	TON (%)	C/N (wt/wt)
HLY0702	28	DLN3	32.78	31.62	10.88	1.83	1.92	1.47	238.39	9.35	5	1.58	0.25	6.39
HLY0702	33	SWC3A	32.70	33.61	12.37	1.89	1.51	6.36	361.12	7.22	5	0.78	0.13	5.91
HLY0702	35	SIL2	32.32	40.16	15.82	1.97	1.86	5.32	409.27	19.25	5	0.54	0.09	5.90
HLY0702	37	NEC2.5	33.00	35.04	14.47	1.92	1.88	6.56	500.37	28.57	4	0.74	0.05	13.94
HLY0702	38	NEC2	33.13	29.24	9.66	1.48	1.03	13.36	222.16	13.25	3	0.33	0.06	5.77
HLY0702	59	KIV4	32.44	22.68	5.39	1.29	0.73	26.68	778.14	5.98	3	0.21	0.06	3.60
HLY0702	60	KIV5	32.35	11.89	3.45	1.02	2.40	21.00	497.73	22.21	3	0.22	0.06	3.62
HLY0702	61	NOM5	32.82	15.52	5.94	1.44	2.94	24.36	327.27	40.55	3	0.20	0.06	3.67
HLY0702	62	NOM4	32.53	23.49	6.30	1.29	0.88	25.60	944.61	14.45	3	0.17	0.05	3.33
HLY0702	63	NOM3	32.66	33.77	10.35	1.51	1.65	10.96	518.73	7.19	3	0.18	0.05	3.54
HLY0702	64	NOM2	32.73	41.20	15.66	1.88	0.98	4.92	258.11	17.24	3	0.53	0.10	5.35
HLY0702	66	RUS1	32.71	38.78	16.43	1.76	1.33	6.96	281.61	23.08	5	0.55	0.09	6.00
HLY0702	67	RUS2	32.73	39.67	17.82	1.93	4.39	4.48	398.57	19.45	3	0.60	0.10	5.92
HLY0702	70	KNG3	32.49	13.55	3.44	0.90	0.53	23.92	962.08	20.32	3	0.37	0.07	5.20
HLY0702	71	RUS4A	32.68	33.54	10.63	1.51	1.99	14.60	835.12	20.84	3	0.47	0.09	5.34
HLY0702	72	KNG2	32.67	38.94	13.70	1.47	1.75	12.28	707.63	20.75	3	0.25	0.06	4.21
HLY0702	73	KNG1	32.67	37.36	16.19	1.31	0.79	6.84	261.74	17.86	4	0.30	0.04	8.05
HLY0702	74	CPW1	32.76	40.51	15.78	1.61	2.38	3.05	296.45	11.46	3	0.24	0.04	6.13

Appendix B. Continued

Cruise	Station Number	Station Name	BW Salinity	Si (µmol L^{-1})	N (µmol L^{-1})	PO4 (µmol L^{-1})	NH4 (µmol L^{-1})	BW Chl *a* (mg m^{-3})	Int Chl *a* (mg m^{-2})	Sed Chl *a* (mg m^{-2})	Sed size (phi)	TOC (%)	TON (%)	C/N (wt/wt)
HLY0702	75	CPW2	32.68	32.97	10.64	1.58	2.14	17.88	1073.98	10.62	3	0.54	0.08	6.95
HLY0702	76	CPW3	32.45	5.96	2.32	1.13	0.44	27.52	1076.43	27.27	3	1.44	0.22	6.50
HLY0702	110	VNG5	32.66	42.96	16.67	2.14	3.17	3.92	332.57	11.43	5	1.57	0.29	5.45
HLY0702	111	NWC2.5	32.57	42.25	16.63	2.07	3.16	3.99	472.53	11.43	5	1.47	0.24	6.21
HLY0702	113	VNG4	32.73	42.05	14.76	2.10	3.48	3.02	107.65	12.73	5	1.48	0.23	6.30
HLY0702	114	CD1	32.77	48.73	16.11	2.13	3.20	6.88	301.48	22.76	5	1.34	0.22	5.99
HLY0702	115	VNG3.5	32.80	46.72	15.71	2.07	3.38	2.50	272.36	17.89	5	1.15	0.16	7.05
HLY0702	116	SWC3	32.80	44.00	14.61	1.98	3.63	4.88	183.09	33.31	5	1.06	0.16	6.61
HLY0702	118	SEC2.5	32.85	36.44	12.42	2.00	3.65	6.64	149.77	34.74	4	0.39	0.06	6.17
HLY0702	120	NEC2.5	33.09	17.47	4.64	1.30	1.81	6.48	186.31	22.37	4	0.74	0.05	13.94
HLY0702	121	NEC2	32.95	10.60	6.31	1.40	2.19	19.00	425.11	40.13	3	0.33	0.06	5.77
HLY0702	137	NEC3	32.96	10.77	2.99	1.16	1.34	10.56	60.91	14.38	5	0.65	0.09	7.24
HLY0702	138	SEC4	32.74	25.41	6.16	1.45	3.26	3.84	64.44	7.40	5	0.53	0.07	7.85
HLY0702	140	SIL5	32.33	39.21	10.11	1.85	4.35	1.36	138.24	10.19	5	0.78	0.11	7.33
HLY0702	141	SWC5	32.55	34.78	10.74	1.60	3.91	1.49	157.46	7.98	5	0.96	0.13	7.69
HLY0702	142	VNG1	32.49	44.38	13.56	1.90	3.47	1.81	178.75	9.87	5	1.02	0.14	7.07
HLY0702	143	NWC5	32.45	45.32	13.54	1.96	3.43	1.34	219.87	16.82	5	1.02	0.14	7.07
HLY0702	144	DLN5	32.59	46.71	15.60	2.02	2.78	1.94	254.44	11.07	5	1.88	0.27	6.85

Appendix B. Continued

Cruise	Station Number	Station Name	BW Salinity	Si (μmol L^{-1})	N (μmol L^{-1})	PO4 (μmol L^{-1})	NH4 (μmol L^{-1})	BW Chl *a* (mg m^{-3})	Int Chl *a* (mg m^{-2})	Sed Chl *a* (mg m^{-2})	Sed size (phi)	TOC (%)	TON (%)	C/N (wt/wt)
HLY0702	115	VNG3.5	32.80	46.72	15.71	2.07	3.38	2.50	272.36	17.89	5	1.15	0.16	7.05
HLY0702	116	SWC3	32.80	44.00	14.61	1.98	3.63	4.88	183.09	33.31	5	1.06	0.16	6.61
HLY0702	118	SEC2.5	32.85	36.44	12.42	2.00	3.65	6.64	149.77	34.74	4	0.39	0.06	6.17
HLY0702	120	NEC2.5	33.09	17.47	4.64	1.30	1.81	6.48	186.31	22.37	4	0.74	0.05	13.94
HLY0702	121	NEC2	32.95	10.60	6.31	1.40	2.19	19.00	425.11	40.13	3	0.33	0.06	5.77
HLY0702	137	NEC3	32.96	10.77	2.99	1.16	1.34	10.56	60.91	14.38	5	0.65	0.09	7.24
HLY0702	138	SEC4	32.74	25.41	6.16	1.45	3.26	3.84	64.44	7.40	5	0.53	0.07	7.85
HLY0702	140	SIL5	32.33	39.21	10.11	1.85	4.35	1.36	138.24	10.19	5	0.78	0.11	7.33
HLY0702	141	SWC5	32.55	34.78	10.74	1.60	3.91	1.49	157.46	7.98	5	0.96	0.13	7.69
HLY0702	142	VNG1	32.49	44.38	13.56	1.90	3.47	1.81	178.75	9.87	5	1.02	0.14	7.07
HLY0702	143	NWC5	32.45	45.32	13.54	1.96	3.43	1.34	219.87	16.82	5	1.02	0.14	7.07
HLY0702	144	DLN5	32.59	46.71	15.60	2.02	2.78	1.94	254.44	11.07	5	1.88	0.27	6.85
HLY0702	145	DLN4	32.61	39.15	14.06	1.79	2.48	2.29	211.42	35.42	5	1.00	0.17	5.87
HLY0702	146	NWC4	32.61	30.67	9.85	1.44	3.17	2.87	147.71	13.96	5	1.32	0.18	7.34

Appendix C. Trawl type, distance, time and area trawled during USCGC *Healy* cruises 2006 (HLY0601) and 2007 (HLY0702)

Cruise	Station Number	Station Name	Trawl Type	Date MM/DD/YYYY	Trawl Start Time	Trawl Distance (m)	Trawl Area (m^2)
HLY0601	1	NEC5	Otter	5/9/2006	10:40	1836.6	6299
HLY0601	2	SEC5	Otter	5/9/2006	20:45	1775.8	6091
HLY0601	3	SIL5	Otter	5/10/2006	3:20	1911.3	6556
HLY0601	4	SWC5	Otter	5/10/2006	9:36	1384.1	4747
HLY0601	6	NWC5	Otter	5/10/2006	20:57	618.3	2121
HLY0601	7	DLN5	Otter	5/11/2006	3:44	726.4	2492
HLY0601	8	NWC4	Otter	5/11/2006	18:20	575.0	1972
HLY0601	11	SWC4	Otter	5/12/2006	8:56	358.4	1229
HLY0601	12	SIL4	Otter	5/12/2006	14:57	774.4	2656
HLY0601	13	SEC4	Otter	5/12/2006	21:02	1557.5	5342
HLY0601	14	NEC4	Otter	5/13/2006	2:39	1415.3	4854
HLY0601	15	SIL3	Otter	5/13/2006	10:25	1485.9	5097
HLY0601	16	POP4	Otter	5/13/2006	15:52	1412.2	4844
HLY0601	17	SWC4A	Otter	5/13/2006	22:12	1452.0	4980
HLY0601	18	SWC3	Otter	5/14/2006	4:47	1368.3	4693
HLY0601	19	VNG3.5	Otter	5/14/2006	11:51	1382.9	4743
HLY0601	20	CD1	Otter	5/14/2006	17:17	827.0	2836
HLY0601	21	VNG4	Otter	5/14/2006	23:05	758.0	2600
HLY0601	22	NWC3	Otter	5/15/2006	3:38	800.4	2745
HLY0601	23	DLN3	Otter	5/15/2006	8:52	927.9	3183
HLY0601	29	SWC3A	Otter	5/17/2006	9:58	892.5	3061
HLY0601	30	POP3A	Otter	5/17/2006	15:08	1354.0	4644
HLY0601	31	SEC2.5	Otter	5/17/2006	19:48	1726.6	5922
HLY0601	32	SEC3	Otter	5/18/2006	0:48	1919.5	6584
HLY0601	36	SEC2	Otter	5/18/2006	21:48	1489.7	5110

Appendix C. Continued

Cruise	Station Number	Station Name	Trawl Type	Date MM/DD/YYYY	Trawl Start Time	Trawl Distance (m)	Trawl Area (m^2)
HLY0601	37	SIL2	Otter	5/19/2006	3:07	1528.8	5244
HLY0601	39	VNG5	Otter	5/19/2006	14:17	480.5	1648
HLY0601	40	NWC2	Otter	5/19/2006	17:21	609.5	2090
HLY0601	44	KIV1	Otter	5/20/2006	12:02	865.2	2968
HLY0601	46	KIV3	Otter	5/20/2006	22:22	1532.4	5256
HLY0601	50	NOM4	Otter	5/21/2006	19:22	1477.9	5069
HLY0601	51	NOM3	Otter	5/21/2006	23:19	1135.1	3893
HLY0601	53	NOM1	Otter	5/22/2006	8:32	569.0	1952
HLY0601	54	RUS1	Otter	5/22/2006	13:17	823.1	2823
HLY0601	55	RUS2	Otter	5/22/2006	19:38	926.5	3178
HLY0601	59	KNG1	Otter	5/23/2006	15:30	1022.8	3508
HLY0601	60	CPW1	Otter	5/23/2006	20:21	871.2	2988
HLY0601	61	KNG2	Otter	5/24/2006	0:48	871.3	2989
HLY0601	63	KNG3	Otter	5/24/2006	10:29	578.6	1985
HLY0601	64	CPW3	Otter	5/24/2006	17:02	1227.8	4211
HLY0601	83	NEC1	Otter	5/27/2006	11:16	682.2	2340
HLY0601	84	SEC1	Otter	5/27/2006	16:32	766.8	2630
HLY0601	85	SEC2	Otter	5/27/2006	20:50	1092.9	3748
HLY0601	86	NEC5A	Otter	5/28/2006	7:48	1579.3	5417
HLY0601	87	SEC4	Otter	5/28/2006	12:51	1838.5	6306
HLY0601	88	SIL4	Otter	5/28/2006	17:55	1313.2	4504
HLY0601	89	POP4	Otter	5/28/2006	23:04	626.3	2148
HLY0601	90	SWC3A	Otter	5/29/2006	3:15	1264.3	4337
HLY0601	96	VNG5	Otter	5/29/2006	20:26	377.7	1295
HLY0601	97	NWC2.5	Otter	5/30/2006	0:45	967.0	3317
HLY0601	98	NWC2	Otter	5/30/2006	5:36	608.3	2086
HLY0601	104	VNG4	Otter	5/31/2006	13:18	373.4	1281

Appendix C. Continued

Cruise	Station Number	Station Name	Trawl Type	Date MM/DD/YYYY	Trawl Start Time	Trawl Distance (m)	Trawl Area (m^2)
HLY0601	105	CD1	Otter	5/31/2006	17:07	369.3	1267
HLY0601	106	SWC4A	Otter	5/31/2006	21:17	378.1	1297
HLY0601	107	VNG3.5	Otter	6/1/2006	1:45	436.1	1496
HLY0601	108	NWC3	Otter	6/1/2006	6:59	496.2	1702
HLY0601	109	DLN3	Otter	6/1/2006	11:29	340.0	1166
HLY0601	110	NWC4	Otter	6/1/2006	17:08	479.1	1643
HLY0601	111	NWC5	Otter	6/1/2006	23:25	388.3	1332
HLY0601	112	VNG1	Otter	6/2/2006	3:43	416.8	1429
HLY0702	1	NEC5	Beam	5/18/2007	8:36	1407.3	5629
HLY0702	6	NWC5	Beam	5/19/2007	13:29	1503.0	6012
HLY0702	7	DLN5	Beam	5/20/2007	0:36	310.0	1240
HLY0702	8	DLN4	Beam	5/20/2007	6:52	299.0	1196
HLY0702	9	NWC4	Beam	5/20/2007	13:24	322.5	1290
HLY0702	12	VNG3.5	Beam	5/21/2007	1:14	695.5	2782
HLY0702	13	SWC4A	Beam	5/21/2007	6:00	444.8	1779
HLY0702	14	SWC4	Beam	5/21/2007	12:14	794.1	3176
HLY0702	15	SIL4	Beam	5/21/2007	18:23	716.5	2866
HLY0702	16	SEC4	Beam	5/21/2007	23:16	1430.8	5723
HLY0702	17	NEC4	Beam	5/22/2007	4:10	823.3	3293
HLY0702	18	NEC3	Beam	5/22/2007	12:29	1254.2	5017
HLY0702	19	SEC3	Beam	5/22/2007	18:51	1349.0	5396
HLY0702	19	SEC3	Otter	5/22/2007	20:05	1550.7	5319
HLY0702	20	SEC2.5	Beam	5/23/2007	0:53	708.7	2835
HLY0702	21	POP3A	Beam	5/23/2007	5:13	490.5	1962
HLY0702	22	SIL3	Beam	5/23/2007	10:26	554.1	2216
HLY0702	23	POP4	Beam	5/23/2007	15:27	590.5	2362
HLY0702	23	POP4	Otter	5/23/2007	16:11	699.7	2400

Appendix C. Continued

Cruise	Station Number	Station Name	Trawl Type	Date MM/DD/YYYY	Trawl Start Time	Trawl Distance (m)	Trawl Area (m^2)
HLY0702	24	SWC3	Beam	5/23/2007	20:49	355.1	1421
HLY0702	25	CD1	Beam	5/24/2007	2:07	193.1	772
HLY0702	26	VNG4	Beam	5/24/2007	7:38	173.1	692
HLY0702	26	VNG4	Otter	5/24/2007	8:20	131.4	451
HLY0702	27	NWC3	Beam	5/24/2007	14:05	212.1	849
HLY0702	28	DLN3	Beam	5/24/2007	19:36	133.9	536
HLY0702	28	DLN3	Otter	5/24/2007	20:25	126.3	433
HLY0702	30	NWC2.5	Beam	5/25/2007	8:23	87.2	349
HLY0702	31	NWC2	Beam	5/25/2007	14:37	52.6	210
HLY0702	33	SWC3A	Beam	5/26/2007	0:37	360.6	1442
HLY0702	35	SIL2	Beam	5/26/2007	10:47	409.0	1636
HLY0702	36	SEC2	Beam	5/26/2007	16:45	666.0	2664
HLY0702	36	SEC2	Otter	5/26/2007	17:23	619.8	2126
HLY0702	37	NEC2.5	Beam	5/26/2007	21.39	367.3	1260
HLY0702	38	NEC2	Beam	5/27/2007	2:18	460.9	1844
HLY0702	56	KIV1	Beam	5/29/2007	7:11	575.7	2303
HLY0702	58	KIV3	Otter	5/29/2007	17:03	507.0	1739
HLY0702	59	KIV4	Beam	5/29/2007	22:00	807.7	3231
HLY0702	60	KIV5	Beam	5/30/2007	3:05	529.0	2116
HLY0702	61	NOM5	Beam	5/30/2007	9:13	379.2	1517
HLY0702	62	NOM4	Beam	5/30/2007	17:40	354.5	1418
HLY0702	62	NOM4	Otter	5/30/2007	18:08	349.4	1198
HLY0702	63	NOM3	Beam	5/31/2007	0:08	162.9	652
HLY0702	64	NOM2	Beam	5/31/2007	4:38	207.7	831
HLY0702	66	RUS1	Beam	5/31/2007	14:56	499.7	1999
HLY0702	66	RUS1	Otter	5/31/2007	15:44	498.7	1711
HLY0702	67	RUS2	Beam	5/31/2007	21:35	242.3	969

Appendix C. Continued

Cruise	Station Number	Station Name	Trawl Type	Date MM/DD/YYYY	Trawl Start Time	Trawl Distance (m)	Trawl Area (m^2)
HLY0702	68	RUS3	Otter	6/1/2007	4:33	214.4	735
HLY0702	70	KNG3	Beam	6/1/2007	16:12	461.8	1847
HLY0702	71	RUS4A	Beam	6/1/2007	23:03	167.2	669
HLY0702	71	RUS4A	Otter	6/1/2007	23:42	142.4	488
HLY0702	72	KNG2	Beam	6/2/2007	3:12	126.3	505
HLY0702	73	KNG1	Beam	6/2/2007	9:53	153.6	615
HLY0702	73	KNG1	Otter	6/2/2007	10:19	229.8	788
HLY0702	74	CPW1	Beam	6/2/2007	14:56	192.3	769
HLY0702	75	CPW2	Beam	6/2/2007	19:40	157.8	631
HLY0702	75	CPW2	Otter	6/2/2007	20:19	158.5	544
HLY0702	76	CPW3	Beam	6/3/2007	1:11	120.3	481
HLY0702	76	CPW3	Otter	6/3/2007	1:55	153.4	526
HLY0702	109	NWC2	Beam	6/6/2007	10:23	368.9	1476
HLY0702	110	VNG5	Beam	6/6/2007	14:45	421.9	1687
HLY0702	111	NWC2.5	Beam	6/6/2007	19:55	419.3	1677
HLY0702	113	VNG4	Beam	6/7/2007	3:28	402.7	1611
HLY0702	114	CD1	Beam	6/7/2007	7:53	299.8	1199
HLY0702	114	CD1	Otter	6/7/2007	8:38	380.5	1305
HLY0702	115	VNG3.5	Beam	6/7/2007	17:17	437.5	1750
HLY0702	116	SWC3	Beam	6/7/2007	22:19	499.0	1996
HLY0702	118	SEC2.5	Beam	6/8/2007	7:33	338.0	1352
HLY0702	118	SEC2.5	Otter	6/8/2007	8:16	504.2	1730
HLY0702	120	NEC2.5	Beam	6/8/2007	19:22	380.2	1521
HLY0702	120	NEC2.5	Otter	6/8/2007	20:01	434.4	1490
HLY0702	121	NEC2	Beam	6/9/2007	1:10	426.1	1705
HLY0702	137	NEC3	Beam	6/10/2007	10:07	487.7	1951
HLY0702	137	NEC3	Beam	6/10/2007	10:54	507.9	2032

Appendix C. Continued

Cruise	Station Number	Station Name	Trawl Type	Date MM/DD/YYYY	Trawl Start Time	Trawl Distance (m)	Trawl Area (m^2)
HLY0702	137	NEC3	Beam	6/10/2007	13:43	505.2	2021
HLY0702	137	NEC3	Beam	6/10/2007	14:31	497.5	1990
HLY0702	138	SEC4	Beam	6/10/2007	21:25	749.9	3000
HLY0702	138	SEC4	Beam	6/10/2007	23:11	694.0	2776
HLY0702	138	SEC4	Beam	6/11/2007	0:07	766.2	3065
HLY0702	138	SEC4	Beam	6/11/2007	1:01	782.7	3131
HLY0702	138	SEC4	Beam	6/11/2007	1:47	763.3	3053
HLY0702	139	SEC5	Beam	6/11/2007	7:43	227.9	912
HLY0702	140	SIL5	Beam	6/11/2007	13:21	463.6	1854
HLY0702	141	SWC5	Beam	6/11/2007	18:37	416.8	1667
HLY0702	142	VNG1	Beam	6/11/2007	23:52	283.9	1136
HLY0702	143	NWC5	Beam	6/12/2007	3:23	287.5	1150
HLY0702	144	DLN5	Beam	6/12/2007	8:17	372.7	1491
HLY0702	145	DLN4	Beam	6/12/2007	13:53	504.3	2017
HLY0702	146	NWC4	Beam	6/12/2007	20:13	465.2	1861
HLY0702	146	NWC4	Otter	6/12/2007	21:07	492.0	1688

Appendix D. Abundance and biomass for groundfish catch for stations trawled from USCGC *Healy* cruise in 2006 (HLY0601). All fish data were collected with an otter trawl

Station Number	Station Name	Common Name	Scientific Name	Number of Fish	Biomass (g)
1	NEC5	Alaska plaice	*Pleuronectes quadrituberculatus*	1	332
		Snailfish	Liparidae	2	24.1
2	SEC5	Alaska plaice	*Pleuronectes quadrituberculatus*	1	356
		Bering flounder	*Hippoglossoides robustus*	1	48.6
		Walleye pollock	*Theragra chalcogramma*	1	2.9
3	SIL5	Alaska plaice	*Pleuronectes quadrituberculatus*	1	252
		Arctic cod	*Boreogadus saida*	1	6.4
		Bering flounder	*Hippoglossoides robustus*	1	32
		Walleye pollock	*Theragra chalcogramma*	7	17.8
4	SWC5			0	0
6	NWC5	Bering flounder	*Hippoglossoides robustus*	1	32
		Snailfish	Liparidae	1	3.8
		Walleye pollock	*Theragra chalcogramma*	1	2.5
7	DLN5	Arctic cod	*Boreogadus saida*	1	8.2
		Bering flounder	*Hippoglossoides robustus*	4	636
		Capelin	*Mallotus villosus*	1	11.1
		Wattled eelpout	*Lycodes palearis*	4	25.5
8	NWC4	Arctic alligatorfish	*Ulcina olrikii*	1	3.1
		Bering flounder	*Hippoglossoides robustus*	4	207
		Poachers	Agonidae	1	0.4
		Snailfish	Liparidae	3	34.2
		Walleye pollock	*Theragra chalcogramma*	5	16.1
11	SWC4	Arctic cod	*Boreogadus saida*	5	77.8
		Walleye pollock	*Theragra chalcogramma*	2	4.9

Appendix D. Continued

Station Number	Station Name	Common Name	Scientific Name	Number of Fish	Biomass (g)
12	SIL4	Arctic cod	*Boreogadus saida*	2	45.1
		Snailfish	Liparidae	1	10.3
		Walleye pollock	*Theragra chalcogramma*	4	11.5
		Yellowfin sole	*Limanda aspera*	1	128
13	SEC4	Bering flounder	*Hippoglossoides robustus*	1	42
		Flounder juv.	Pleuronectidae	1	0.4
		Pacific cod	*Gadus macrocephalus*	1	14.8
		Plain sculpin	*Myoxocephalus jaok*	1	708
		Smelts juv.	Osmeridae	1	1.2
		Snailfish	Liparidae	17	168.5
		Walleye pollock	*Theragra chalcogramma*	2	5.7
		Yellowfin sole	*Limanda aspera*	1	96
14	NEC4	Arctic cod	*Boreogadus saida*	2	45.4
15	SIL3	Arctic alligaterfish	*Ulcina olrikii*	3	5.1
		Arctic cod	*Boreogadus saida*	1	20.7
		Capelin	*Mallotus villosus*	1	10.8
		Snailfish	Liparidae	6	32.1
		Walleye pollock	*Theragra chalcogramma*	1	2
16	POP4	Snailfish	Liparidae	6	32.4
		Walleye pollock	*Theragra chalcogramma*	1	2.8
17	SWC4A	Arctic cod	*Boreogadus saida*	5	94.8
		Bering flounder	*Hippoglossoides robustus*	1	10.8
		Snailfish	Liparidae	4	41.2
		Walleye pollock	*Theragra chalcogramma*	2	5.2
18	SWC3	Arctic cod	*Boreogadus saida*	15	308.3
		Bering flounder	*Hippoglossoides robustus*	6	155.3
		Snailfish	Liparidae	1	9.7

Appendix D. Continued

Station Number	Station Name	Common Name	Scientific Name	Number of Fish	Biomass (g)
19	VNG3.5	Arctic cod	*Boreogadus saida*	25	496.4
		Bering flounder	*Hippoglossoides robustus*	7	176
		Snailfish	Liparidae	6	39.5
		Stout eelblenny	*Anisarchus medius*	2	4.3
		Veteran poacher	*Podothecus veternus*	1	28
		Walleye pollock	*Theragra chalcogramma*	1	10.2
20	CD1	Arctic cod	*Boreogadus saida*	17	347.3
		Bering flounder	*Hippoglossoides robustus*	3	70.5
		Snailfish	Liparidae	2	7.8
		Stout eelblenny	*Anisarchus medius*	2	7.5
		Walleye pollock	*Theragra chalcogramma*	2	6.8
21	VNG4	Arctic cod	*Boreogadus saida*	4	92.7
		Bering flounder	*Hippoglossoides robustus*	3	169.7
		Snailfish	Liparidae	2	11.3
		Walleye pollock	*Theragra chalcogramma*	2	4.7
22	NWC3	Arctic cod	*Boreogadus saida*	2	28.6
		Eelpouts, unid	Zoarcidae	1	84
		Walleye pollock	*Theragra chalcogramma*	1	4.7
23	DLN3	Arctic cod	*Boreogadus saida*	6	60.9
		Bering flounder	*Hippoglossoides robustus*	5	346.7
		Snailfish	Liparidae	3	20.8
		Stout eelblenny	*Anisarchus medius*	1	6.2
29	SWC3A	Arctic cod	*Boreogadus saida*	21	427.5
		Bering flounder	*Hippoglossoides robustus*	1	39.7
		Pacific hering	*Clupea pallasii*	1	11.5
		Snailfish	Liparidae	5	43.3
		Walleye pollock	*Theragra chalcogramma*	1	5.6

Appendix D. Continued

Station Number	Station Name	Common Name	Scientific Name	Number of Fish	Biomass (g)
30	POP3A	Arctic alligaterfish	*Ulcina olrikii*	2	5.4
		Arctic cod	*Boreogadus saida*	5	91.9
		Bering flounder	*Hippoglossoides robustus*	1	26.4
		Snailfish	Liparidae	2	2.9
		Walleye pollock	*Theragra chalcogramma*	1	4
31	SEC2.5	Arctic alligaterfish	*Ulcina olrikii*	4	7.3
		Snailfish	Liparidae	1	2.5
		Walleye pollock	*Theragra chalcogramma*	1	2.4
32	SEC3	Alaska plaice	*Pleuronectes quadrituberculatus*	1	382
		Arctic alligaterfish	*Ulcina olrikii*	1	2.4
		Arctic staghorn sculpin	*Gymnocanthus tricuspis*	1	4.6
		Snailfish	Liparidae	1	1.4
		Yellowfin sole	*Limanda aspera*	1	115.3
36	SEC2	Arctic alligaterfish	*Ulcina olrikii*	7	11.37
		Arctic cod	*Boreogadus saida*	1	40.9
		Arctic staghorn sculpin	*Gymnocanthus tricuspis*	1	11.7
		Capelin	*Mallotus villosus*	3	32.9
		Longhead dab	*Limanda proboscidea*	1	270
		Shorthorn sculpin	*Myoxocephalus scorpius*	1	101.5
		Snailfish	Liparidae	1	15
		Walleye pollock	*Theragra chalcogramma*	1	3.5
37	SIL2	Arctic alligaterfish	*Ulcina olrikii*	2	3.5
		Arctic cod	*Boreogadus saida*	11	261.3
		Arctic staghorn sculpin	*Gymnocanthus tricuspis*	1	14.2
		Bering flounder	*Hippoglossoides robustus*	2	50.4
		Poachers, unid	Agonidae	1	1.7
		Veteran poacher	*Podothecus veternus*	3	61.5
39	VNG5	Arctic cod	*Boreogadus saida*	2	47.5
		Walleye pollock	*Theragra chalcogramma*	1	2

Appendix D. Continued

Station Number	Station Name	Common Name	Scientific Name	Number of Fish	Biomass (g)
40	NWC2	Arctic cod	*Boreogadus saida*	53	896.4
		Bering flounder	*Hippoglossoides robustus*	3	93.5
		Snailfish	Liparidae	1	4
44	KIV1	Arctic cod	*Boreogadus saida*	2	36.7
		Arctic staghorn sculpin	*Gymnocanthus tricuspis*	2	27.4
		Capelin	*Mallotus villosus*	1	3.2
46	KIV3	Arcitc alligatorfish	*Ulcina olrikii*	2	3
		Arctic cod	*Boreogadus saida*	3	65.5
		Shorthorn sculpin	*Myoxocephalus scorpius*	12	7193
		Veteran poacher	*Podothecus veternus*	1	14.9
		Walleye pollock	*Theragra chalcogramma*	2	7.6
50	NOM4	Alligatorfish	*Aspidophoroides monopterygius*	1	2.4
		Arcitc alligatorfish	*Ulcina olrikii*	21	47.8
		Arctic staghorn sculpin	*Gymnocanthus tricuspis*	5	133.4
		Bering flounder	*Hippoglossoides robustus*	1	29.8
		Eyeshade sculpin	*Nautichthys pribilovius*	1	4
		Sculpin, unid	Cottidae	2	12.2
		Snailfish	Liparidae	1	1.8
		Veteran poacher	*Podothecus veternus*	2	27.4
51	NOM3	Arcitc alligatorfish	*Ulcina olrikii*	3	8.6
		Arctic cod	*Boreogadus saida*	7	153
		Arctic staghorn sculpin	*Gymnocanthus tricuspis*	6	187.4
		Butterfly sculpin	*Hemilepidotus papilio*	1	7.2
		Sculpin, unid	Cottidae	1	8
		Snailfish	Liparidae	2	65.5
		Veteran poacher	*Podothecus veternus*	1	15.4
53	NOM1	Pacific sand lance	*Ammodytes hexapterus*	1	5.5

Appendix D. Continued

Station Number	Station Name	Common Name	Scientific Name	Number of Fish	Biomass (g)
54	RUS1	Arcitc alligatorfish	*Ulcina olrikii*	3	2.2
		Arctic cod	*Boreogadus saida*	4	77.2
		Bering flounder	*Hippoglossoides robustus*	6	189.7
		Snailfish	Liparidae	1	2.4
		Veteran poacher	*Podothecus veternus*	2	38.3
55	RUS2	Arctic cod	*Boreogadus saida*	1	11.6
		Bering flounder	*Hippoglossoides robustus*	3	85.8
59	KNG1	Alligatorfish	*Aspidophoroides monopterygius*	2	1.1
		Arcitc alligatorfish	*Ulcina olrikii*	31	35.8
		Arctic cod	*Boreogadus saida*	20	354.3
		Arctic staghorn sculpin	*Gymnocanthus tricuspis*	20	300.8
		Bering flounder	*Hippoglossoides robustus*	3	52.9
		Eyeshade sculpin	*Nautichthys pribilovius*	1	2.3
		Flounder juv.	Pleuronectidae	2	0.4
		Sculpin, unid	Cottidae	1	0.2
60	CPW1	Alligatorfish	*Aspidophoroides monopterygius*	1	0.6
		Arcitc alligatorfish	*Ulcina olrikii*	23	34.4
		Arctic cod	*Boreogadus saida*	30	548.2
		Arctic staghorn sculpin	*Gymnocanthus tricuspis*	39	334.7
		Flounder juv.	Pleuronectidae	4	6.1
		Sculpin, unid	Cottidae	6	23.8
		Snailfish	Liparidae	3	11.9
61	KNG2	Alligatorfish	*Aspidophoroides monopterygius*	1	1.2
		Arcitc alligatorfish	*Ulcina olrikii*	8	12.8
		Arctic cod	*Boreogadus saida*	18	344.9
		Arctic staghorn sculpin	*Gymnocanthus tricuspis*	38	555.4
		Bering flounder	*Hippoglossoides robustus*	19	424.9
		Veteran poacher	*Podothecus veternus*	1	20.8
63	KNG3	Arctic cod	*Boreogadus saida*	1	15.1

Appendix D. Continued

Station Number	Station Name	Common Name	Scientific Name	Number of Fish	Biomass (g)
64	CPW3	Arcitc alligatorfish	*Ulcina olrikii*	7	15.5
		Arctic cod	*Boreogadus saida*	1	31.9
		Arctic staghorn sculpin	*Gymnocanthus tricuspis*	13	447.1
		Bering flounder	*Hippoglossoides robustus*	2	67.5
		Snailfish	Liparidae	2	22.2
		Yellowfin sole	*Limanda aspera*	1	7.9
83	NEC1	Arctic cod	*Boreogadus saida*	7	130.5
		Walleye pollock	*Theragra chalcogramma*	2	10.2
85	SEC2	Arcitc alligatorfish	*Ulcina olrikii*	2	3.3
		Shorthorn sculpin	*Myoxocephalus scorpius*	1	494
86	NEC5A	Snailfish	Liparidae	1	2.3
		Walleye pollock	*Theragra chalcogramma*	1	3
87	SEC4	Alaska plaice	*Pleuronectes quadrituberculatus*	2	312
		Arctic cod	*Boreogadus saida*	2	41.7
		Pacific cod	*Gadus macrocephalus*	1	24.2
		Shorthorn sculpin	*Myoxocephalus scorpius*	1	620
		Snailfish	Liparidae	1	9.1
88	SIL4	Arctic cod	*Boreogadus saida*	27	525.2
		Bering flounder	*Hippoglossoides robustus*	1	32.7
		Pacific herring	*Clupea pallasii*	5	644
		Sakhalin flounder	*Limanda sakhalinensis*	1	29.3
		Snailfish	Liparidae	6	62.4
		Walleye pollock	*Theragra chalcogramma*	12	38.2
89	POP4	Arctic cod	*Boreogadus saida*	10	184.3
		Sakhalin flounder	*Limanda sakhalinensis*	1	31.3
		Snailfish	Liparidae	1	15
		Veteran poacher	*Podothecus veternus*	1	18.1

Appendix D. Continued

Station Number	Station Name	Common Name	Scientific Name	Number of Fish	Biomass (g)
96	VNG5	Arctic cod	*Boreogadus saida*	9	128.9
		Bering flounder	*Hippoglossoides robustus*	8	357.1
		Snailfish	Liparidae	2	5
		Stout eelblenny	*Anisarchus medius*	1	8.2
97	NWC2.5	Alligatorfish	*Aspidophoroides monopterygius*	1	1.7
		Arctic cod	*Boreogadus saida*	4	73.6
		Bering flounder	*Hippoglossoides robustus*	1	32.5
		Polar eelpout	*Lycodes polaris*	1	7.5
98	NWC2	Arctic cod	*Boreogadus saida*	3	55.8
		Bering flounder	*Hippoglossoides robustus*	4	177
		Polar eelpout	*Lycodes polaris*	1	10.3
		Snailfish	Liparidae	1	6.3
		Walleye pollock	*Theragra chalcogramma*	2	6.8
104	VNG4	Arctic cod	*Boreogadus saida*	11	174.5
		Bering flounder	*Hippoglossoides robustus*	4	79.1
		Snailfish	Liparidae	2	22.8
105	CD1	Arctic cod	*Boreogadus saida*	16	236.7
		Bering flounder	*Hippoglossoides robustus*	3	77.4
		Picklebacks, unid	Stichaeidae	1	0.48
		Shorthorn sculpin	*Myoxocephalus scorpius*	1	450
106	SWC4A	Arctic cod	*Boreogadus saida*	15	257.8
		Bering flounder	*Hippoglossoides robustus*	5	354.1
		Snailfish	Liparidae	1	17.5
		Veteran poacher	*Podothecus veternus*	1	14.1
		Yellowfin sole	*Limanda aspera*	1	160.4
107	VNG3.5	Arctic cod	*Boreogadus saida*	11	195.6
		Bering flounder	*Hippoglossoides robustus*	7	258.5
		Snailfish	Liparidae	2	19.9

Appendix D. Continued

Station Number	Station Name	Common Name	Scientific Name	Number of Fish	Biomass (g)
108	NWC3			0	0
109	DLN3	Arctic cod	*Boreogadus saida*	4	67.4
		Bering flounder	*Hippoglossoides robustus*	5	382.7
		Snake prickleback	*Lumpenus sagitta*	1	8.1
		Stout eelblenny	*Anisarchus medius*	2	13.6
110	NWC4	Arctic cod	*Boreogadus saida*	3	27.5
		Bering flounder	*Hippoglossoides robustus*	3	96.8
		Pacific herring	*Clupea pallasii*	1	7.2
		Stout eelblenny	*Anisarchus medius*	3	17.1
111	NWC5	Arctic cod	*Boreogadus saida*	7	153.9
		Bering flounder	*Hippoglossoides robustus*	1	27.1
112	VNG1	Arctic cod	*Boreogadus saida*	4	132.2
		Capelin	*Mallotus villosus*	1	13.7
		Walleye pollock	*Theragra chalcogramma*	1	3.4

Appendix E. Abundance and biomass for groundfish catch for stations trawled from USCGC *Healy* cruise in 2007 (HLY0702). Key: Station number is formed with three digit number of station number, B = beam trawl or O = otter trawl

Station Number	Station Name	Common Name	Scientific Name	Number of Fish	Biomass (g)
001B	NEC5	Arctic cod	*Boreogadus saida*	5	148
		Pacific cod	*Gadus Macrocephalus*	1	12
		Snailfish	Liparidae	3	33
006B	NWC5	Arctic cod	*Boreogadus saida*	7	106
		Bering flounder	*Hippoglossoides robustus*	6	556
		Snailfish	Liparidae	5	74
		Stout eelblenny	*Anisarchus medius*	3	19
007B	DLN5	Bering flounder	*Hippoglossoides robustus*	3	136
		Snailfish	Liparidae	5	110
008B	DLN4	Arcitc alligatorfish	*Ulcina olrikii*	4	6
		Bering flounder	*Hippoglossoides robustus*	10	422
		Snailfish	Liparidae	6	70
		Wattled eelpout	*Lycodes palearis*	4	16
009B	NWC4			0	0
012B	VNG3.5	Arctic cod	*Boreogadus saida*	1	5
		Bering flounder	*Hippoglossoides robustus*	2	69
		Snailfish	Liparidae	12	127
		Spatulate sculpin	*Icelus spatula*	1	1
		Flounder juv.	Pleuronectidae	1	1
		Veteran poacher	*Podothecus veternus*	1	29
013B	SWC4A	Arctic cod	*Boreogadus saida*	1	4
		Bering flounder	*Hippoglossoides robustus*	1	35
		Snailfish	Liparidae	3	33
		Wattled eelpout	*Lycodes palearis*	1	5
014B	SWC4	Arcitc alligatorfish	*Ulcina olrikii*	1	2
		Bering flounder	*Hippoglossoides robustus*	1	107

Appendix E. Continued

Station Number	Station Name	Common Name	Scientific Name	Number of Fish	Biomass (g)
014B	SWC4	Pacific cod	*Gadus Macrocephalus*	1	19
		Snailfish	Liparidae	1	14
015B	SIL4	Arctic cod	*Boreogadus saida*	1	48
		Snailfish	Liparidae	1	49
016B	SEC4	Bering flounder	*Hippoglossoides robustus*	2	72
		Snailfish	Liparidae	3	49
017B	NEC4	Arctic cod	*Boreogadus saida*	1	61
		Bering flounder	*Hippoglossoides robustus*	2	52
		Snailfish	Liparidae	3	44
018B	NEC3			0	0
019B	SEC3			0	0
019O	SEC3	Alaska Plaice	*Pleuronectes quadrituberculatus*	1	148
		Arcitc alligatorfish	*Ulcina olrikii*	2	4
		Arctic cod	*Boreogadus saida*	12	26
		Bering flounder	*Hippoglossoides robustus*	5	6
		Snailfish	Liparidae	14	69
		Spatulate sculpin	*Icelus spatula*	2	2
		Unid.		5	5
020B	SEC2.5	Arcitc alligatorfish	*Ulcina olrikii*	1	3
		Bering flounder	*Hippoglossoides robustus*	1	40
021B	POP3A	Bering flounder	*Hippoglossoides robustus*	4	112
022B	SIL3			0	0
023B	POP4	Bering flounder	*Hippoglossoides robustus*	1	1
		Snailfish	Liparidae	1	12
023O	POP4	Arctic cod	*Boreogadus saida*	8	29

Appendix E. Continued

Station Number	Station Name	Common Name	Scientific Name	Number of Fish	Biomass (g)
023O	POP4	Snailfish	Liparidae	5	19
		Picklebacks, unid	Stichaeidae	1	1
024B	SWC3	Bering flounder	*Hippoglossoides robustus*	2	58
025B	CD1	Arctic cod	*Boreogadus saida*	2	15
		Bering flounder	*Hippoglossoides robustus*	1	33
		Snailfish	Liparidae	2	50
026B	VNG4	Bering flounder	*Hippoglossoides robustus*	2	29
		Snailfish	Liparidae	6	26
026O	VNG4	Arctic cod	*Boreogadus saida*	1	3
027B	NWC3	Bering flounder	*Hippoglossoides robustus*	1	105
		Snailfish	Liparidae	2	10
		Picklebacks, unid	Stichaeidae	4	4
028B	DLN3	Bering flounder	*Hippoglossoides robustus*	1	43
		Snailfish	Liparidae	2	14
		Picklebacks, unid	Stichaeidae	1	1
028O	DLN3	Snailfish	Liparidae	12	69
030B	NWC2.5	Picklebacks, unid	Stichaeidae	1	1
031B	NWC2			0	0
033B	SWC3A	Arctic cod	*Boreogadus saida*	1	3
		Bering flounder	*Hippoglossoides robustus*	5	82
		Snailfish	Liparidae	2	37
035B	SIL2	Snailfish	Liparidae	1	21
036B	SEC2			0	0

Appendix E. Continued

Station Number	Station Name	Common Name	Scientific Name	Number of Fish	Biomass (g)
036O	SEC2	Arcitc alligatorfish	*Ulcina olrikii*	3	3
		Arctic cod	*Boreogadus saida*	8	24
		Bering flounder	*Hippoglossoides robustus*	22	26
		Snailfish	Liparidae	2	12
		Spatulate sculpin	*Icelus spatula*	13	13
		Unidentified		1	1
037B	SEC2.5	Bering flounder	*Hippoglossoides robustus*	1	2
038B	NEC2	Bering flounder	*Hippoglossoides robustus*	1	1
056B	KIV1			0	0
058O	KIV3	Arcitc alligatorfish	*Ulcina olrikii*	4	8
		Arctic cod	*Boreogadus saida*	1	3
		Arctic staghorn sculpin	*Gymnocanthus tricuspis*	7	41
		Pacific cod	*Gadus Macrocephalus*	2	18
		Sculpin, unid	Cottidae	3	9
		Shorthorn sculpin	*Myoxocephalus scorpius*	67	28392
		Walleye pollock	*Theragra chalcogramma*	2	9
059B	KIV4	Arcitc alligatorfish	*Ulcina olrikii*	2	6
		Arctic staghorn sculpin	*Gymnocanthus tricuspis*	2	46
		Bering flounder	*Hippoglossoides robustus*	1	28
		Pacific cod	*Gadus Macrocephalus*	1	8
		Veteran poacher	*Podothecus veternus*	1	1
		Yellowfin sole	*Limanda aspera*	1	2
060B	KIV5	Bering flounder	*Hippoglossoides robustus*	2	4
061B	NOM5	Arctic cod	*Boreogadus saida*	1	20
062B	NOM4	Arctic staghorn sculpin	*Gymnocanthus tricuspis*	1	18
062O	NOM4	Arcitc alligatorfish	*Ulcina olrikii*	7	18
		Arctic staghorn sculpin	*Gymnocanthus tricuspis*	1	6

Appendix E. Continued

Station Number	Station Name	Common Name	Scientific Name	Number of Fish	Biomass (g)
062O	NOM4	Shorthorn sculpin	*Myoxocephalus scorpius*	1	3
		Snailfish	Liparidae	1	6
063B	NOM3	Arcitc alligatorfish	*Ulcina olrikii*	1	2
		Arctic staghorn sculpin	*Gymnocanthus tricuspis*	1	9
		Sculpin, unid	Cottidae	1	7
		Shorthorn sculpin	*Myoxocephalus scorpius*	6	4273
064B	NOM2	Bering flounder	*Hippoglossoides robustus*	1	44
		Shorthorn sculpin	*Myoxocephalus scorpius*	2	764
066B	RUS1	Shorthorn sculpin	*Myoxocephalus scorpius*	9	2715
066O	RUS1	Bering flounder	*Hippoglossoides robustus*	3	7
		Shorthorn sculpin	*Myoxocephalus scorpius*	15	4809
		Snailfish	Liparidae	1	11
		Walleye pollock	*Theragra chalcogramma*	1	3
067B	RUS2	Shorthorn sculpin	*Myoxocephalus scorpius*	13	4619
068O	RUS3	Arcitc alligatorfish	*Ulcina olrikii*	1	3
		Arctic staghorn sculpin	*Gymnocanthus tricuspis*	1	16
		Shorthorn sculpin	*Myoxocephalus scorpius*	2	1004
		Snailfish	Liparidae	1	5
070B	KNG3	Arctic cod	*Boreogadus saida*	1	38
		Bering flounder	*Hippoglossoides robustus*	2	26
071B	RUSA	Shorthorn sculpin	*Myoxocephalus scorpius*	1	756
		Veteran poacher	*Podothecus veternus*	1	31
071O	RUSA	Arcitc alligatorfish	*Ulcina olrikii*	3	6
		Arctic cod	*Boreogadus saida*	3	45
		Bering flounder	*Hippoglossoides robustus*	1	1
072B	KNG2	Arcitc alligatorfish	*Ulcina olrikii*	1	3

Appendix E. Continued

Station Number	Station Name	Common Name	Scientific Name	Number of Fish	Biomass (g)
072B	KNG2	Bering flounder	*Hippoglossoides robustus*	1	35
		Snailfish	Liparidae	1	26
073B	KNG1	Arctic staghorn sculpin	*Gymnocanthus tricuspis*	3	27
		Snailfish	Liparidae	1	23
073O	KNG1	Arcitc alligatorfish	*Ulcina olrikii*	4	7
		Arctic cod	*Boreogadus saida*	4	11
		Arctic staghorn sculpin	*Gymnocanthus tricuspis*	3	22
		Bering flounder	*Hippoglossoides robustus*	2	4
		Shorthorn sculpin	*Myoxocephalus scorpius*	3	992
		Snailfish	Liparidae	2	12
		Spatulate sculpin	*Icelus spatula*	1	1
		Walleye pollock	*Theragra chalcogramma*	3	10
074B	CPW1	Arcitc alligatorfish	*Ulcina olrikii*	7	80
		Shorthorn sculpin	*Myoxocephalus scorpius*	1	379
075B	CPW2	Arcitc alligatorfish	*Ulcina olrikii*	1	3
		Arctic staghorn sculpin	*Gymnocanthus tricuspis*	3	48
		Bering flounder	*Hippoglossoides robustus*	1	5
		Veteran poacher	*Podothecus veternus*	1	9
075O	CPW2	Arcitc alligatorfish	*Ulcina olrikii*	3	8
		Arctic cod	*Boreogadus saida*	4	131
		Arctic staghorn sculpin	*Gymnocanthus tricuspis*	10	128
		Shorthorn sculpin	*Myoxocephalus scorpius*	1	27
		Snailfish	Liparidae	1	4
		Spatulate sculpin	*Icelus spatula*	1	3
		Walleye pollock	*Theragra chalcogramma*	1	4
		Wattled eelpout	*Lycodes palearis*	1	10
		Yellowfin sole	*Limanda aspera*	1	95
076B	CPW3	Arctic cod	*Boreogadus saida*	1	39
		Bering flounder	*Hippoglossoides robustus*	3	117
		Scalybreasted sculpin	*Triglops xenostethus*	1	11

Appendix E. Continued

Station Number	Station Name	Common Name	Scientific Name	Number of Fish	Biomass (g)
076O	CPW3	Arcitc alligatorfish	*Ulcina olrikii*	1	1
		Arctic cod	*Boreogadus saida*	1	2
		Arctic staghorn sculpin	*Gymnocanthus tricuspis*	2	10
		Bering flounder	*Hippoglossoides robustus*	4	124
		Saddled eelpout	*Lycodes mucosus*	2	22
		Scalybreasted sculpin	*Triglops xenostethus*	1	11
		Shorthorn sculpin	*Myoxocephalus scorpius*	7	28
		Snailfish	Liparidae	2	45
		Veteran poacher	*Podothecus veternus*	1	7
		Wattled eelpout	*Lycodes palearis*	9	82
109B	NWC2			0	0
110B	VNG5	Arctic cod	*Boreogadus saida*	1	5
		Bering flounder	*Hippoglossoides robustus*	1	24
		Polar eelpout	*Lycodes polaris*	1	1
		Snailfish	Liparidae	2	20
		Stout eelblenny	*Anisarchus medius*	1	4
111B	NWC2.5	Arctic cod	*Boreogadus saida*	3	17
		Bering flounder	*Hippoglossoides robustus*	1	24
		Snailfish	Liparidae	6	36
		Picklebacks, unid	Stichaeidae	4	4
113B	VNG4	Bering flounder	*Hippoglossoides robustus*	6	326
		Snailfish	Liparidae	6	82
114B	CD1	Bering flounder	*Hippoglossoides robustus*	1	24
		Picklebacks, unid	Stichaeidae	1	1
		Snailfish	Liparidae	3	40
114O	CD1	Alaska plaice	*Pleuronectes quadrituberculatus*	1	175
		Arctic cod	*Boreogadus saida*	6	34
		Bering flounder	*Hippoglossoides robustus*	8	466
		Picklebacks, unid	Stichaeidae	1	1
		Snailfish	Liparidae	20	166
		Stout eelblenny	*Anisarchus medius*	1	5

Appendix E. Continued

Station Number	Station Name	Common Name	Scientific Name	Number of Fish	Biomass (g)
115B	VNG3.5	Arctic cod	*Boreogadus saida*	1	51
		Bering flounder	*Hippoglossoides robustus*	4	68
		Sculpin, unid	Cottidae	1	1
		Snailfish	Liparidae	4	31
116B	SWC3	Bering flounder	*Hippoglossoides robustus*	4	125
		Snailfish	Liparidae	2	31
118B	SEC2.5	Bering flounder	*Hippoglossoides robustus*	1	31
118O	SEC2.5	Arcitc alligatorfish	*Ulcina olrikii*	2	4
		Arctic cod	*Boreogadus saida*	2	5
		Bering flounder	*Hippoglossoides robustus*	2	31
		Snailfish	Liparidae	5	31
		Walleye pollock	*Theragra chalcogramma*	1	5
120B	NEC2.5	Alaska plaice	*Pleuronectes quadrituberculatus*	1	144
		Alligatorfish	*Aspidophoroides monopterygius*	1	1
		Bering flounder	*Hippoglossoides robustus*	2	11
120O	NEC2.5	Arcitc alligatorfish	*Ulcina olrikii*	1	2
		Arctic cod	*Boreogadus saida*	1	7
		Bering flounder	*Hippoglossoides robustus*	3	3
		Snailfish	Liparidae	1	23
		Unid.		1	1
		Walleye pollock	*Theragra chalcogramma*	10	37
121B	NEC2	Yellowfin sole	*Limanda aspera*	1	57
137B1	NEC3	Alaska plaice	*Pleuronectes quadrituberculatus*	1	121
		Yellowfin sole	*Limanda aspera*	2	301
137B2	NEC3	Bering flounder	*Hippoglossoides robustus*	1	3
137B3	NEC3	Bering flounder	*Hippoglossoides robustus*	1	27
137B4	NEC3	Veteran poacher	*Podothecus veternus*	1	5

Appendix E. Continued

Station Number	Station Name	Common Name	Scientific Name	Number of Fish	Biomass (g)
138B1	SEC4	Arctic cod	*Boreogadus saida*	1	40
		Bering flounder	*Hippoglossoides robustus*	2	107
138B2	SEC4	Bering flounder	*Hippoglossoides robustus*	5	145
138B3	SEC4	Bering flounder	*Hippoglossoides robustus*	3	136
		Pacific herring	*Clupea pallasii*	1	78
		Sakhalin sole	*Limanda sakhalinensis*	1	40
		Snailfish	Liparidae	3	62
138B4	SEC4	Bering flounder	*Hippoglossoides robustus*	3	121
		Snailfish	Liparidae	2	63
138B5	SEC4	Bering flounder	*Hippoglossoides robustus*	2	118
		Walleye pollock	*Theragra chalcogramma*	1	5
139B	SEC5			0	0
140B	SIL5	Sakhalin sole	*Limanda sakhalinensis*	1	67
		Snailfish	Liparidae	1	10
		Walleye pollock	*Theragra chalcogramma*	1	3
141B	SWC5	Arctic cod	*Boreogadus saida*	1	53
		Bering flounder	*Hippoglossoides robustus*	4	144
		Snailfish	Liparidae	5	91
142B	VNG1	Arctic cod	*Boreogadus saida*	2	76
		Bering flounder	*Hippoglossoides robustus*	3	224
143B	NWC5	Arctic cod	*Boreogadus saida*	2	39
		Bering flounder	*Hippoglossoides robustus*	3	300
		Snailfish	Liparidae	1	28
144B	DLN5	Arctic cod	*Boreogadus saida*	2	75
		Bering flounder	*Hippoglossoides robustus*	8	784
		Wattled eelpout	*Lycodes palearis*	1	78

Appendix E. Continued

Station Number	Station Name	Common Name	Scientific Name	Number of Fish	Biomass (g)
145B	DLN4	Arctic cod	*Boreogadus saida*	2	57
145B	DLN4	Bering flounder	*Hippoglossoides robustus*	1	39
145B	DLN4	Snailfish	Liparidae	8	141
145B	DLN4	Stout eelblenny	*Anisarchus medius*	1	5
146B	NWC4	Bering flounder	*Hippoglossoides robustus*	1	19
146B	NWC4	Snailfish	Liparidae	2	59
146O	NWC4	Bering flounder	*Hippoglossoides robustus*	4	179
146O	NWC4	Snailfish	Liparidae	9	85
146O	NWC4	Stout eelblenny	*Anisarchus medius*	1	4
146O	NWC4	Walleye pollock	*Theragra chalcogramma*	1	9

Vita

Xuehua Cui was born in Yanji, Jilin Province, China on November 8, 1975. She went to Yanbian first high school and obtained a B.S. in Marine Biology at the Ocean University of China in 1997. She studied at the Pukyong National University (Republic of Korea) from 1998 to 2000 and received a M.S. in Marine Biology. She enrolled at the University of Tennessee, Knoxville in spring 2005 and completed her graduate project with the degree of Doctor of Philosophy in Ecology and Evolutionary Biology with a concentration in Marine Ecology and minor in Statistics in summer 2009.